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Robin Edward Shuff

Development of Remote Handling Pipe Jointing Tools for ITER

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Development of Remote Handling Pipe Jointing Tools for ITER

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 30th of March 2012, at 12 noon.

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ABSTRACT

Welding is broadly defined as a *permanent* method of material joining. In the field of Remote Handling (RH) however the combined requirements for high quality joints and regular replacement of high value components and plant on magnetic confinement fusion machines have resulted in a situation where welding is customarily treated as a reversible joining method with the use of cutting tools. This atypical usage of welding requires a range of sophisticated tooling for cutting, refurbishment, metrology, alignment and re-welding operations. In the past, on projects where RH has been used extensively such the Joint European Torus (JET) the technical demands of this approach were met by adopting a conservative design rationale; joint designs were simplified to the point where autogenous single pass welds on thin walled pipes could be used. Thin walled pipes also permit the use of thin walled bellows adding compliance to the system and thus assisting joint fit up.

The RH pipe jointing requirements of future fusion machines like ITER are such that the conditions described for JET will not necessarily be possible, consequently a more sophisticated suite of RH jointing tooling is anticipated. Larger pipe wall thicknesses have been cited as part of the ITER design; this may necessitate multiple pass welding which has an associated increased risk of producing an unacceptable joint. Pipes with larger wall thicknesses have less compliance which complicates fit-up prior to re-welding. Mechanical cutting methods carry a risk of causing distortion to pipe ends during cutting and release of weld stresses, furthermore larger wall thicknesses make the correction of such deformations more difficult. Other complications associated with mechanical cutting and welding include the refurbishment and inspection of cut edges prior to re-welding and the risk of tool jamming/failure during cutting. Material lost during the cutting process must also be accommodated somehow in subsequent joining operations. This in addition to the need to re-weld outside the heat affected zone of the previous weld limits the number of re-welding operations that can be performed for a given component.

In response to the problems of applying welding and cutting principals to the pipe jointing requirements of ITER and future fusion machines, this body of research considers a diverse range of alternative pipe jointing technologies applicable to RH. Brazing was selected as the most promising research domain. Following the development of the necessary theory covering the design of a novel pipe joint system used in combination with an exotic brazing technique, this work has resulted in the successful creation of a revolutionary pipe jointing solution. With the strength of a welded joint but without the complication of using inherently risky mechanical cutting processes for disassembly, the fruits of this research offer valuable benefits to the RH engineer and a diverse range of other pipe jointing applications.

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NOMENCLATURE

A	Area [m^2]
F	Force [N]
p	Pressure [Pa]
k	Stiffness [N/m]
P	Steady force applied to body [N]
δ	Displacement produced by a force [m]
E	Young's Modulus [MPa]
Є	Strain [mm]
v	Poisson’s ratio
C	Specific heat capacity [J/(kgK)]
T	Temperature [K]
P	Power [W]
P	Neutron loading [Wcm^2]
E	Electron volt [eV]
F	Leak rate (flow) [Pa•m^3•sec^{-1}]
P_c	Connecting pressure for SMA pipe fitting [MPa]
P_l	Applied load for convoluted element [N]
P_a	Absorbed power [kW]

Absorbed dose	Gray [Gy]
Dose equivalent	Sievert [Sv]
Radioactive decay	Alpha [α]
	Gamma [γ]

ABBREVIATIONS

A_f	Austenite
ALARA	As Low As Reasonably Achievable
AVC	Automated Arc Voltage Control
BTS	Bore Tool System
CCTR	Cassette Compact Toroid Reactor
CMM	Cassette Multifunctional Mover
CTM	Cassette Toroidal Mover
DTP	Divertor Test Platform in Brasimone, Italy
DTP2	Divertor Test Platform 2 in Tampere, Finland
FEA	Finite Element Analysis
HAZ	Heat Affected Zone
He	Helium
HMI	Human Machine Interface
ICF	Inertial Confinement Fusion
ICRH	Ion Cyclotron Resonance Heating
ICRP	International Commission on Radiological Protection
ID	Inner Diameter
IHA	Department of Intelligent Hydraulics and Automation
ITER	'The way' in Latin, will be the world's largest tokamak nuclear fusion reactor situated in Cadarache, France
IVT	In-Vessel Transporter
IVVS	In Vessel Viewing System
JET	Joint European Torus in Culham, UK.
M_f	Martensite
MCF	Magnetic Confinement Fusion
MIG	Metal Inert Gas
MPD	Multi Purpose Deployer
NB(I)	Neutral Beam (Injection)
NDT	Non Destructive Testing
OD	Outer Diameter
PFC	Plasma Facing Component
PTFE	Ploytetrafluoroethylene, more commonly known as Teflon®
Q	Power Multiplication Factor, used in nuclear engineering

RF	Radio Frequency
RH	Remote Handling
SMA	Shape Memory Alloy
SQL	Structured Query Language
TFTR	Tokamak Fusion Test Reactor in Princeton, NJ, USA
TIG	Tungsten Inert Gas
Tore Supra	Tokamak fusion test reactor in Cadarache, France
TUT	Tampere University of Technology
UHV	Ultra High Vacuum
UKEA	United Kingdom Atomic Energy Authority
US	Ultra Sonic (Inspection)
UTS	Ultimate Tensile Strength [MPa]
VR	Virtual Reality
VTT	Technical Research Centre of Finland
VV	Vacuum Vessel
WHMAN	Water Hydraulic Manipulator
YAG	Yttrium Aluminium Garnet

1 INTRODUCTION

Vertut defines Remote Handling (RH) as the technology that allows human operators to safely and reliably perform manipulation of items without being in personal contact with those items [Vertut 1986]. RH methods are employed in a diverse range of industries such as sub-sea and medicine in situations where hands-on human interaction with the task is desirable but prevented by hazardous environments or a lack of human strength or dexterity. RH is most synonymous with the nuclear fusion and fission; used in applications such as maintaining fusion machines, processing of fuel assemblies or in Hot Cell environments for manipulating irradiated materials.

RH tasks are performed by a combination of movers, servo-manipulators and dedicated tooling typically operated from a control room environment, see figure 1 taken at Joint European Torus (JET).

Figure 1: RH at JET showing control room environment (left) and RH equipment (right)

Man-in-the-loop control is characteristic of RH whereby human operators control output equipment by entering commands via a Human Machine

Interface (HMI) or a Master/Slave arrangement. Inputs are then processed using real-time control software which in turn manages the necessary power requirements for output equipment.

RH performs an increasingly vital role in fusion power research providing the facility for repair and maintenance of fusion machines. Moreover RH permits potentially unplanned changes to the configuration of experimental fusion machines giving greater flexibility to the direction in which the research can evolve.

Fusion is the process that causes the stars to shine, it occurs when two light nuclei fuse to form a single nucleus liberating some mass in the form of energy.

Nuclei must collide with tremendous energy to satisfy the conditions of nuclear fusion. In the 1950’s efforts began to recreate the conditions necessary to allow fusion reactions to occur in the laboratory. Over the decades fusion research has focussed on two methods; inertial confinement and magnetic confinement.

Inertial Confinement Fusion (ICF) machines initiate fusion reactions by heating and compressing a fuel target or pellet containing a mixture of deuterium and tritium. The input energy is supplied by high power lasers, focussed on the fuel pellet, enclosed inside a vacuum chamber.

Magnetic Confinement Fusion (MFC) research has proceeded apace in parallel with inertial confinement. Magnetic confinement machines, or tokamaks, supply energy to nuclei in the form of heat from a range of sources including Neutral Beam Injection (NBI), ohmic and Radio Frequency (RF) heating.

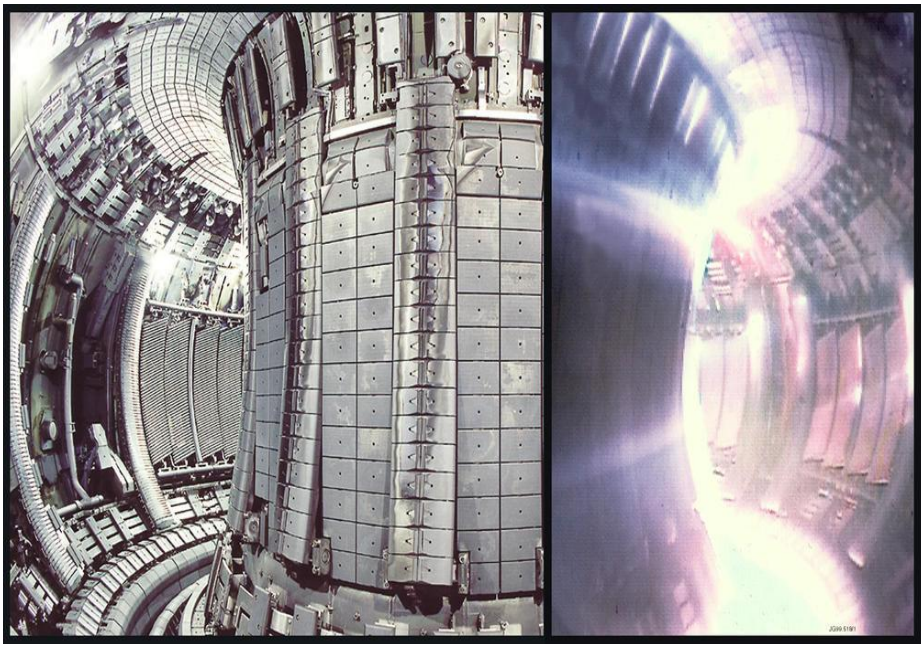


Figure 2: Fusion at JET

Maintaining plasma energy is critical to sustaining fusion reactions. If the plasma comes into contact with the machine walls energy is lost, the hot plasma is extinguished and fusion ceases to occur. To insulate the plasma from the machine walls, the tokamak vessel is evacuated to form an Ultra High Vacuum (UHV). The vessel is then back-filled with the ionised plasma gas which is manipulated away from the machine walls using magnetic fields.

Over the past 50 years research in magnetic confinement fusion has steadily advanced towards the goal of providing the basis for industrial scale electricity generating power plants. As such experimental fusion machines have become more powerful achieving more fusion reactions and liberating more energy resulting in a situation where direct human intervention on the machines is no longer possible due to a hazardous radioactive environment.

The current focus of fusion research is the deuterium ($_2H$) – tritium ($_3H$) reaction:

$$ {}_2\boldsymbol{H} + {}_3\boldsymbol{H} \rightarrow \boldsymbol{He} + \boldsymbol{n} + \boldsymbol{\alpha} + 17.6 \text{ MeV} $$

Equation 1: Deuterium-Tritium Reaction

The reaction produces heliFum (*He*) a high energy neutron (*n*) and alpha radiation (α) with the equivalent kinetic energy of 17.6 million electron volts (MeV) through the loss of mass in the fusion process. The neutrons released cause secondary activation in the fusion machine structure, resulting in a hazardous radioactive environment. For the next generation of experimental fusion machines such as ITER (see figure 3) and for projected future power plants radiation levels will exceed permissible legal exposure limits for manned access by several orders of magnitude. In order to perform in vessel operations and tasks in other hostile areas on the ITER machine, a RH utility has been proposed.

1.1 The Need for Remote Handling in Radiation Environments

In this section the nature of the hazardous environment in which RH methods are used is presented. The effects of radiation on RH equipment is also summarised.

1.1.1 The Nuclear Environment

The primary source of ionising radiation in a fusion reactor is the neutrons produced from the deuterium – tritium reaction, see equation 1. Following a campaign of reactor operations, tokamaks are periodically shut down for maintenance and upgrade tasks. Prior to shut down fusion reactions are stopped, neutrons are no longer produced and their damaging effects are not encountered during interventions inside the reactor.

However the neutrons produced during operations are captured in the materials of the reactor structure and associated components, creating Activation products. Materials containing Activation products exhibit one or more of a range of Radionuclides; atoms with a nucleus characterised by excess energy that is eventually dissipated with the ejection of a particle or electron. With this change in energy state the radionuclide undergoes radioactive decay emitting potentially harmful ionising radiation in the form of gamma rays and other subatomic particles [Holmes-Siedle 2002]

ITER has restricted the highest intensity radiation environment for workers to no more than 100 µSv/h [Uzan-Elbez 2005], with an annual dose no higher than 5 mSv/year. This is in accordance with the rules set out by the International Commission for Radiological Protection (ICRP) which governs radiation workers in Europe recommending that workers should receive a dose rate of no higher than 20 mSv averaged over 5 years where a total dose rate in any one year can be no larger than 50 mSv. In addition to this ITER is obliged to follow the ALARA principal (As Low As Reasonably Achievable) which stipulates that wherever possible the dose rate will be minimised if practical and affordable. By comparison the predicted radiation environment 2 weeks after shutdown inside the Torus is 500 Sv/h, exceeding the dose limit for workers by many orders of magnitude [Tesini 2009].

There are some very basic rules that are followed to ensure worker safety:

Wait; radioactivity decays with time, decay rates can be very significant with activation reducing by many orders of magnitude in the first days or even hours after a reactor is shut down.

Provide shielding; gamma radiation has a very high penetrating power, the use of a shield between the source and the person such as water, boron enriched concrete or lead can provide adequate protection.

Keep maximum distance between the source and the person; this is where Remote Handling comes in.

1.1.2 Other Hazards

Small amounts of tritium will remain inside the reactor following operations posing a contamination threat to operators and the surrounding environment [Di Pace 2008]. Tritium in the form of dust, tritiated water or gas poses a health hazard if inhaled or ingested due to cell damage by the ionising beta radiation emitted during radioactive decay.

Beryllium tiles were used extensively at JET and will potentially be used in some applications on ITER. Beryllium is toxic to humans, if inhaled can cause berylliosis, a dangerous persistent lung disorder that can damage other organs such as the heart.

1.1.3 Radiation Effects on RH Equipment

The dominant radiation parameter for RH equipment working on the tokomak during shutdown periods is the highly penetrating gamma-rays. In general the consequences of irradiating materials are: embrittlement, growth, loss of ductility, creep, and aging. RH equipment is designed to be radiation tolerant principally by selecting materials that are stable under gamma irradiation and by placing sensitive subsystems away from the radiation source. Particularly problematic are electronic items such as cameras or systems that contain integrated circuits, similarly polymers such as electrical insulation degrade in a gamma environment. Generally, materials and electronic components exhibit unique responses to irradiation sources. Critical components must be evaluated under test conditions to determine their performance and life expectancy. Such studies are made in test reactors, long durations are often required, costs are in turn high to the extent they can make a global impact on the cost of a reactor.

1.1.3.1 Metals

The effects of irradiation on metal parts only becomes apparent after long periods of time. Similar metals to those used in the reactor are typically used for Remote Handling equipment. Exposure times however are relatively short and at low levels compared with the structure of the reactor

1.1.3.2 Plastics

Different plastics exhibit different responses to irradiation. Polytetrafluoroethylene (PTFE) has a relatively short life, turning to powder after 100 Gy whereas polyamides such as DuPont™ Zytel® are very high 1 MGy before degradation occurs. Fluorocarbons and halogenated polymers release corrosive gasses that can damage surrounding components. Elastomers, widely used as a sealing medium in mechanical assemblies, must maintain their elastic properties. Polyurethane phenylsilicones Nitrile and styrene butadiene that are generally used for O-rings still have good behaviour up to 1 MGy [Holmes-Siedle 2002].

1.1.3.3 Electrical Components

The durability of electrical wiring is a function of the insulation, embrittlement is a particular problem for robotic applications where wiring is fed through articulating joints. Rad-hardened varnishes for windings such as motors and transformers can with stand high doses of up to 1 MGy. Transducers and processors containing integrated circuits suffer from poor life expectancy due to the poor radiation tolerance of semiconductors. Special motors are used in radiation environments, making use of suitable insulators, lubricants and electrical connectors.

The permissible accumulated doses for common items used in Remote Handling equipment [Holmes-Siedle 2002] are summarised in table 1. Mean values are indicated by the blue bar, the range of deviation from the mean is given by the black marker.

1.1.3.4 ITER Radiation Tolerance Requirements

Radiation environments on the ITER reactor will vary, in-vessel shut down conditions are thought to be in the region of 500 Gy/h for the worst case [Tesini 2005]. Inevitably this will lead to limited life expectancy for some components with vital implications on operational availabiliy of equipment that must be taken into account by the RH engineer, sensitive components will have to be periodically replaced, some technologies previously commonplace in RH will not be applicable for ITER such as certain types of camera for example.

ITER requirements for RH equipment in the Divertor region (see section 1.4) state that sensitive items such as motors, sensors, cameras, lubricants and cables shall have a minimum demonstrated radiation life expectancy of 1 MGy [ITER 2008]. In the case of operations at the Divertor where the radiation environment is predicted to be in the region of 200 Gy/h, this equates to a necessary system life expectancy of 52 weeks, at 7 days/week, 24 hrs/day. This compares to the maximum of 500 Gy/h for interventions immediately or soon after shut down. Operations in the Divertor region would be performed after a period of weeks, when the gamma environment is less harsh.

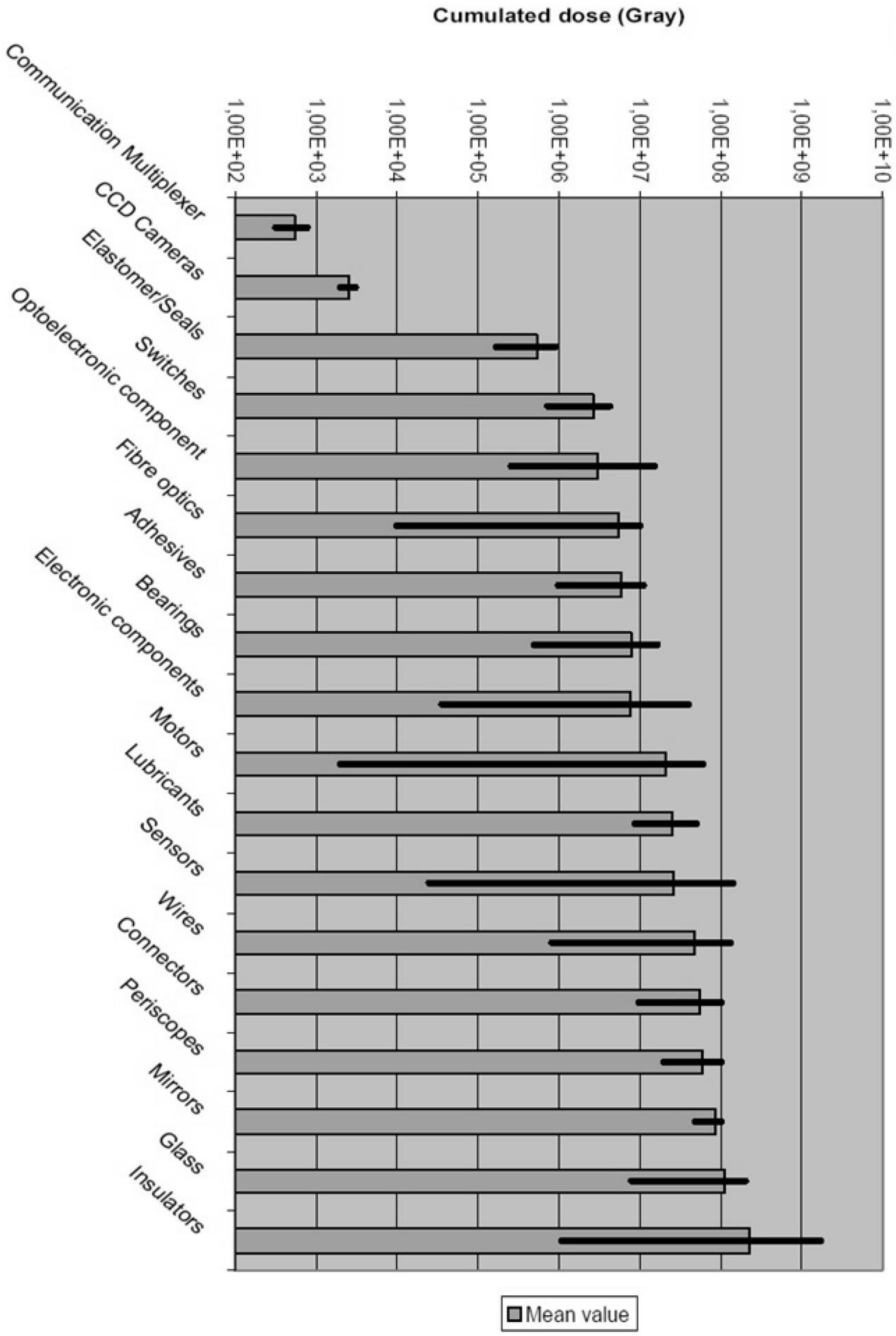


Table 1: Cumulated permissible dose level by component type [Holmes-Siedle 2002]

1.2 ITER

ITER, Latin for ‘the way’ will be the world’s largest experimental tokamak nuclear fusion reactor. Its goal is to test and demonstrate the technologies necessary for an electricity producing nuclear fusion power plant. The scale of the technical challenge this represents has required an international collaboration, with the European Union, India, Japan, China, Russia, South Korea and the United States of America all helping fund and run the project. ITER will rely extensively on RH methods to ensure full operational availability and is therefore of great interest to this research.

1.2.1 The Allure of the ITER Project

Despite its massive cost and technical uncertainties, the potential benefits of fusion power make it an irresistible curiosity. Foremost among these benefits are its ecological credentials. Nuclear fusion does not suffer from the massive pitfall inherent in conventional nuclear fission of dealing with spent nuclear fuel. The exhaust products from nuclear fusion reactions, see equation 1, are energy and helium. Needless to say, fusion does not produce CO_2 or any other atmospheric pollutants. As a caveat the nuclear reactor structure does become activated and is subject to a similar decommissioning headache at the end of plant life as fission.

Another advantage of fusion is its inherent safety. Following operations in a conventional fission reactor, the fuel generates heat due to radioactive decay and must be continually cooled for long periods of time. This requires the constant presence of a coolant typically water, or liquid metal in fast reactors, and a means of dissipating the heat such as a heat exchanger. Should any of these systems fail the fuel and surrounding containment structures are liable to melt risking a hazardous release of radiation products. In short, a nuclear fission plant cannot quite simply be ‘switched off’. The hot fuel demands the reactor or fuel storage systems stay intact for months or years following operations, a vital requirement made only too obvious by the events at

Fukushima in Japan during 2011. In a fusion reactor the precise balance of plasma density and energy must be maintained to create fusion reactions. If the primary vessel containment is breached for whatever reason, the plasma becomes diluted with the ambient gases of the reactor building and fusion reactions cease to occur. Furthermore at any one time the total amount of fuel present in a fusion reactor is in the region of a fraction of a gram, implying that should the containment be breached somehow only a limited release of radiation products would be possible.

The absence of large amounts of fuel inside the reactor at any one time unlike fission reactors greatly reduces the likelihood of a criticality accident in a fusion reactor.

Often overlooked is the relative abundance and even distribution of fusion fuel over the earth's crust. Deuterium is found naturally in water, Lithium (used to make tritium) is also present in water and is known to have an earthly abundance approximately that of Lead. As a consequence no single country or power could hold a monopoly on fuel supply.

1.2.2 The ITER Machine

Work on the ITER site began in 2007 clearing some 90 hectares of land in preparation for building construction. First plasma is scheduled for 2019 when the real work will start on achieving the stated goal of operating at 500 MW power for 1000 s with a power multiplication factor of Q = 10. [ITER 2011]. The ITER torus will have a major and minor radius of 6.2 m and 2 m giving a plasma volume of 837 m^3. This compares with the JET, the largest tokamak currently in existence with major and minor radii of 3 m and 1.25 m, plasma volume of 155 m^3.

The superconducting magnets used to confine and shape the plasma inside the reactor vessel are together the largest and single most costly subsystem in the reactor. They consist of 18 toroidal field coils, a central solenoid, six poloidal coils and 18 correction coils. Despite the plasma temperature reaching nearly 1.5 x 10^8 K, the coils just metres away are cooled with supercritical helium to 4 K.

Before fusion can occur, the plasma must be heated using a range of external means. The magnetic coils and plasma behave like the primary and secondary windings on a transformer. As electric current passes through the conductive plasma, heat is generated. Neutral beam injectors firing a high-energy beam of deuterium atoms into the reactor transfer their energy to the plasma raising the temperature. Other systems transfer energy to the plasma via electromagnetic radiation using various radio frequency heating devices.

The super-heated plasma will be housed in a Stainless Steel vacuum vessel, providing the primary containment between the fusion reactions and the outside world. Weighing some 5000 tons it will feature more than 40 ports to allow maintenance and upgrade operations by Remote Handling and for diagnostic, heating and vacuum systems.

More than 40 diagnostic systems will be installed on the ITER machine to provide the necessary feedback on parameters such as temperature and density to control and evaluate the plasma.

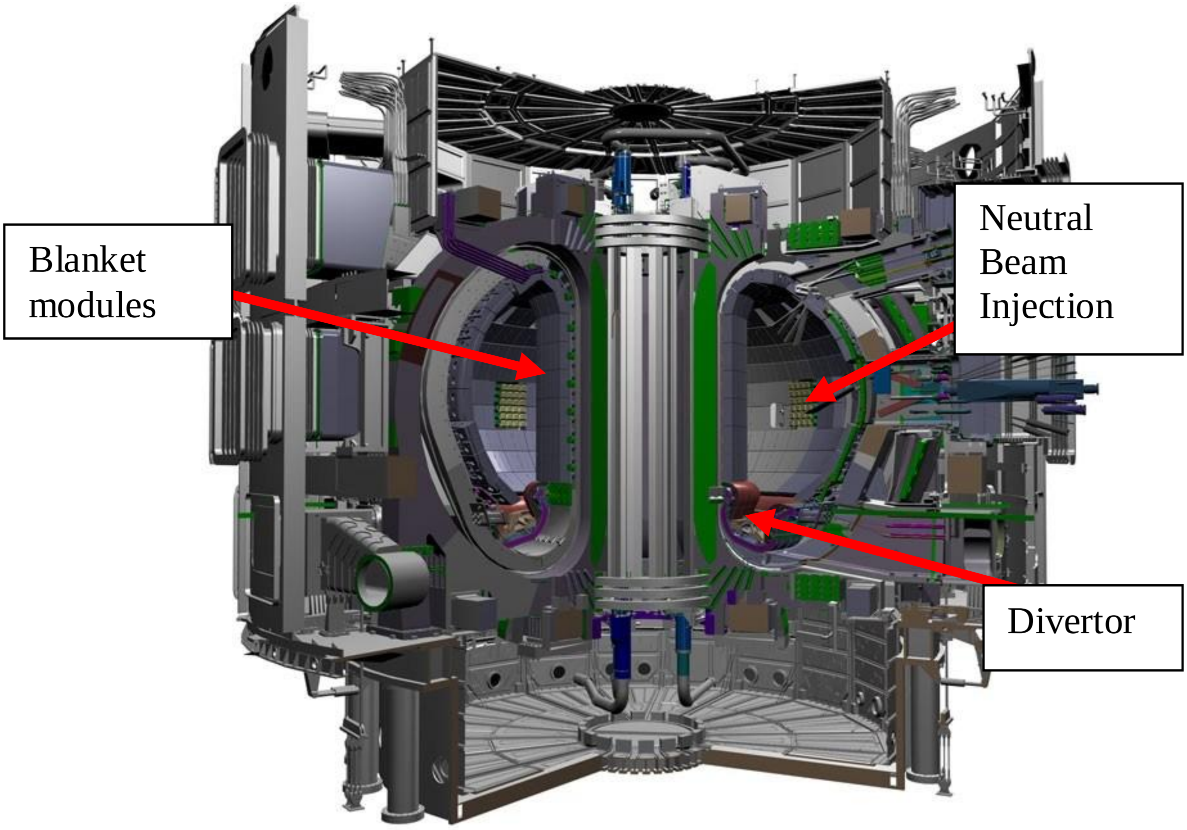


Figure 3: The ITER machine

1.3 Remote Handling at ITER

Design work has begun on the more significant RH tasks for the ITER machine [Honda 2002]. Some examples of typical RH tasks associated with the ITER machine follow:

1.3.1 In Vessel Transporter System

ITER blanket modules line the inside of the reactor providing thermal and nuclear shielding to the machine structure. The modules are expected to be replaced during the lifetime of ITER due to erosion caused by plasma/wall interactions. A rail mounted In Vessel Transporter (IVT) system has been specified featuring a telescopic manipulator for replacing and retrieving blanket modules, see figure 4. The rail is deployed inside the 12 m diameter torus, around which the manipulator can translate, the installation of the rail therefore represents a significant RH task in itself. The water cooled blankets require welding and cutting operations during maintenance to connect to a water supply manifold. Bolting operations are required to attach the modules to the Vacuum Vessel (VV) wall [Kukadate 2008].

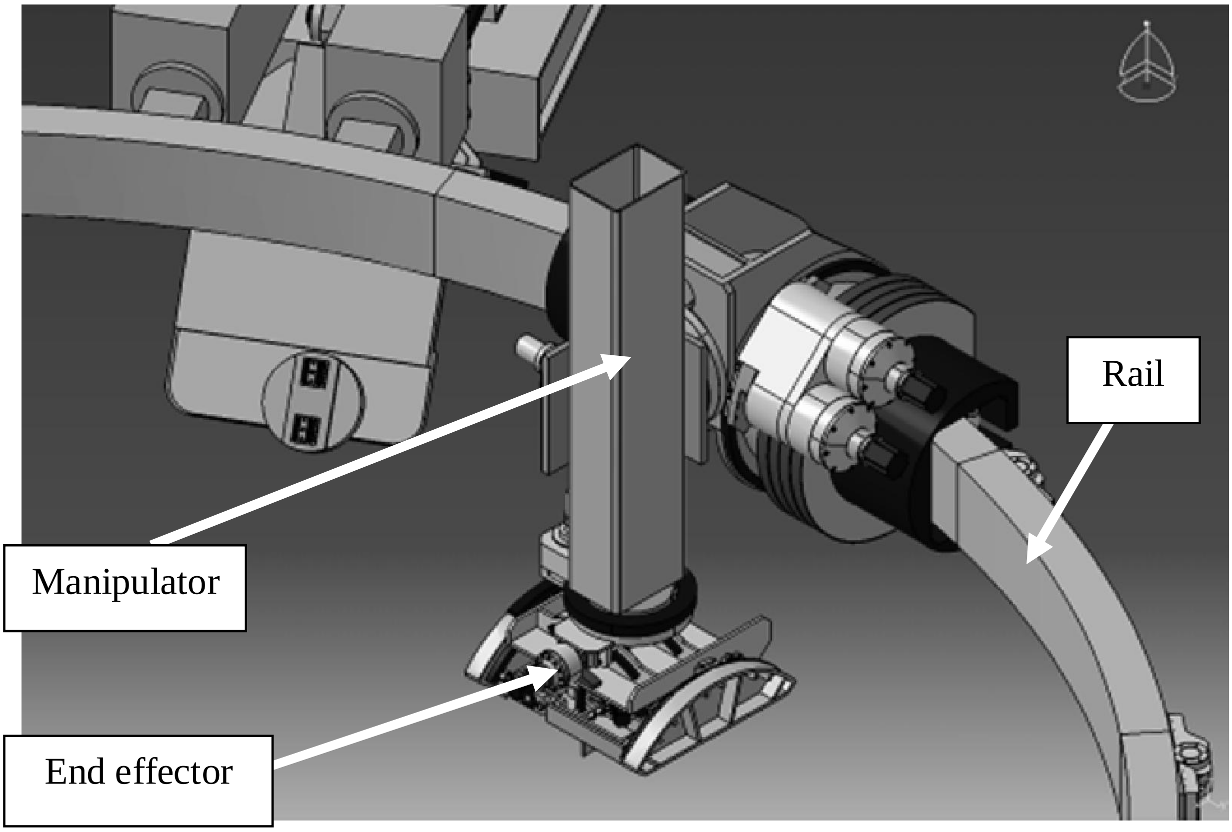


Figure 4: In Vessel Transporter System

1.3.2 Cask Transfer System

A RH Cask Transfer System (CTS) will be used to transport machine components to and from a Hot Cell refurbishment facility, see figure 5. The casks run on an air cushion and are capable of docking with the VV and Hot Cell ports. Components are introduced to the cask using a mover/handling tractor [Tesini 2001].

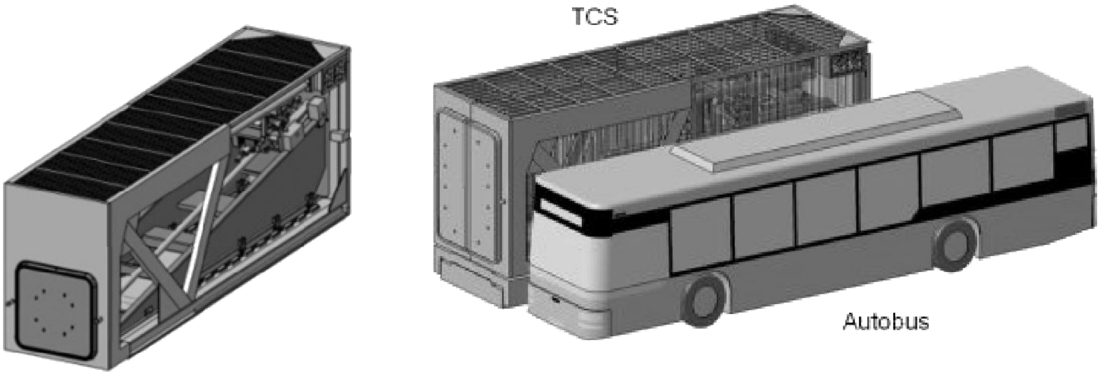


Figure 5: Cask Transfer System (scale illustrated with autobus)

1.3.3 Hot Cell

The ITER Hot Cell provides a refurbishment and storage facility for machine components. Operations inside the Hot Cell are performed entirely remotely using a range of movers, cranes, servo-manipulators and tooling. Commissioning and maintenance of RH equipment, such as boom style transporters, dextrous servo-manipulators, lifting jigs and cleaning equipment will also be performed in the Hot Cell [Locke 2009]. Figure 6 shows the ITER Hot Cell and reactor building, where the Cask Transfer System will be used to move components and RH equipment.

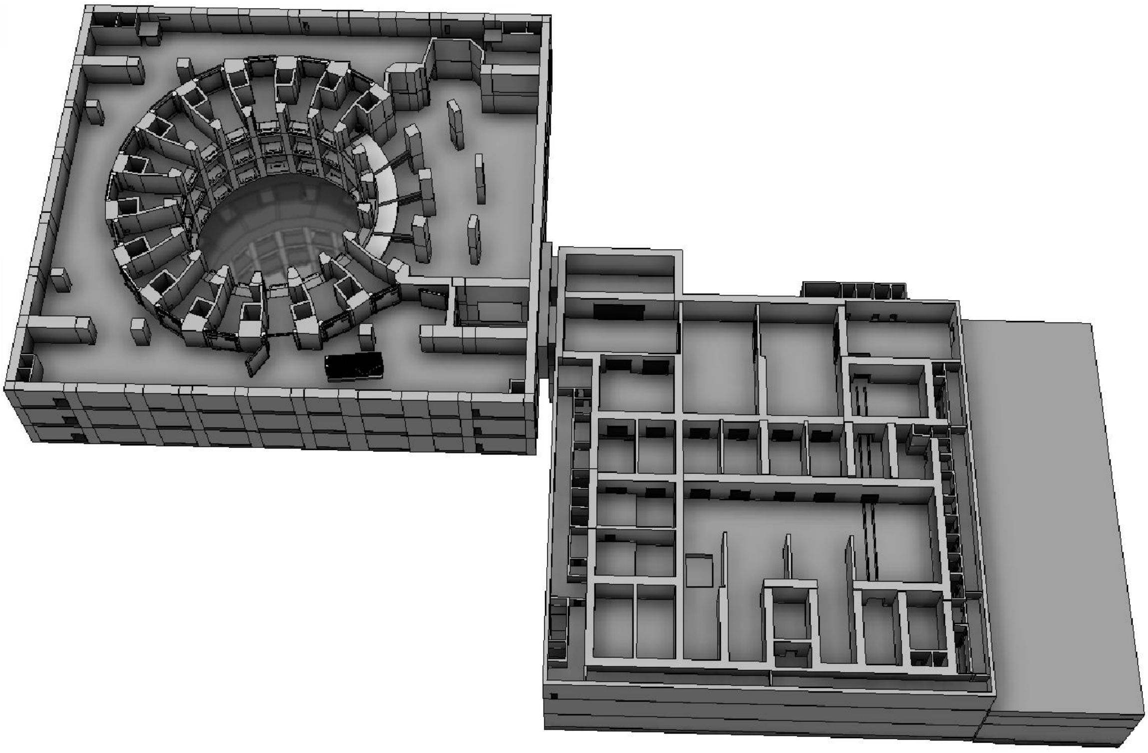


Figure **6**: ITER Hot Cell lower right, adjacent to reactor building upper left

1.3.4 In Vessel Viewing System

An RH in Vessel Viewing System (IVVS) will be used to inspect the inner walls of the Vacuum Vessel and to check for damage caused by plasma/wall interactions, see figure 7. The system will use both optical and laser viewing systems and be capable of operating under post-plasma conditions including high magnetic field and UHV [Perrot 2003].

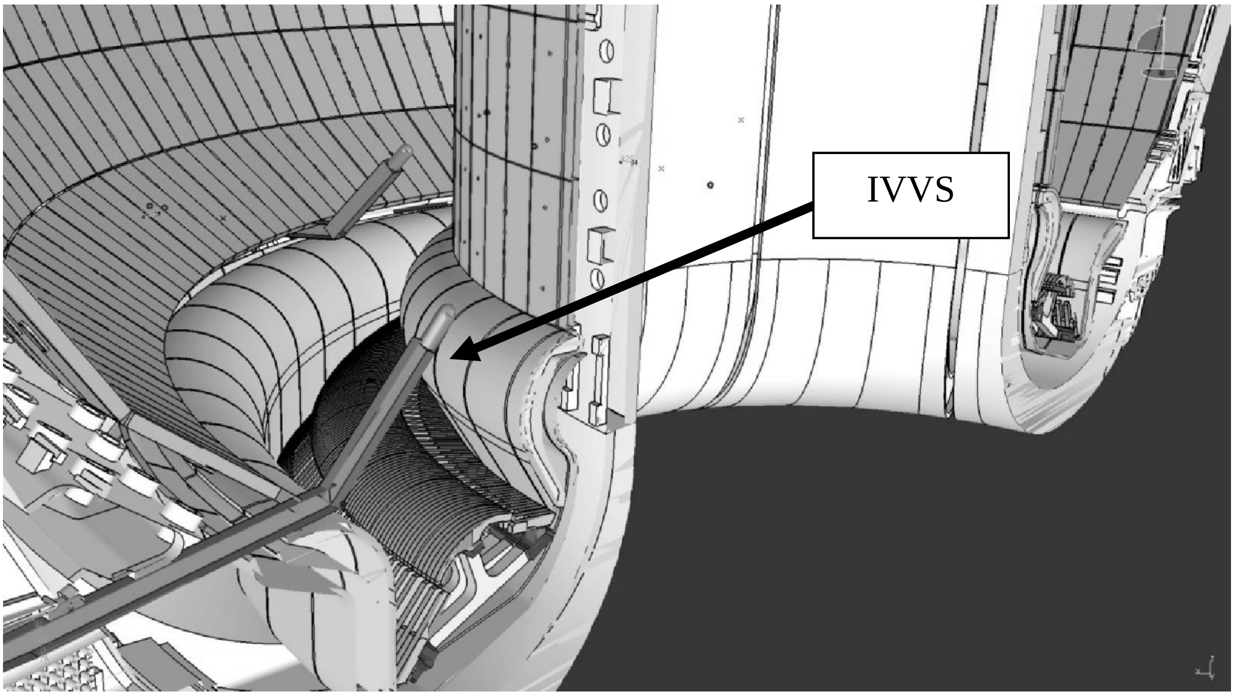


Figure 7: ITER In Vessel Viewing System

1.3.5 Neutral Beam Maintenance

The ITER Neutral Beam (NB) accelerates positive deuterium ions before neutralising them again with the addition of an electron to facilitate their transmission through the magnetic field into the plasma. The system is large and complex, maintenance such as replacement of beam source and accelerator, beam line components and diagnostics will be carried out by servo-manipulator and dedicated tooling. NB operations will also involve welding and cutting of water cooling pipes [Honda 2002].

1.3.6 Multi-Purpose Deployer

The Multi-Purpose Deployer (MPD) will be used to perform tasks inside the VV such as dust monitoring and removal, VV inspection and leak detection. More importantly the MPD will be used to perform unexpected repair and reconfiguration tasks that will inevitably occur on an experimental platform such as ITER.

The MPD will feature a multi-link anthropomorphic arm, see figure 8, with a payload of 2 tons, capable of placing dextrous manipulators along with components and tools at any location inside the VV torus.

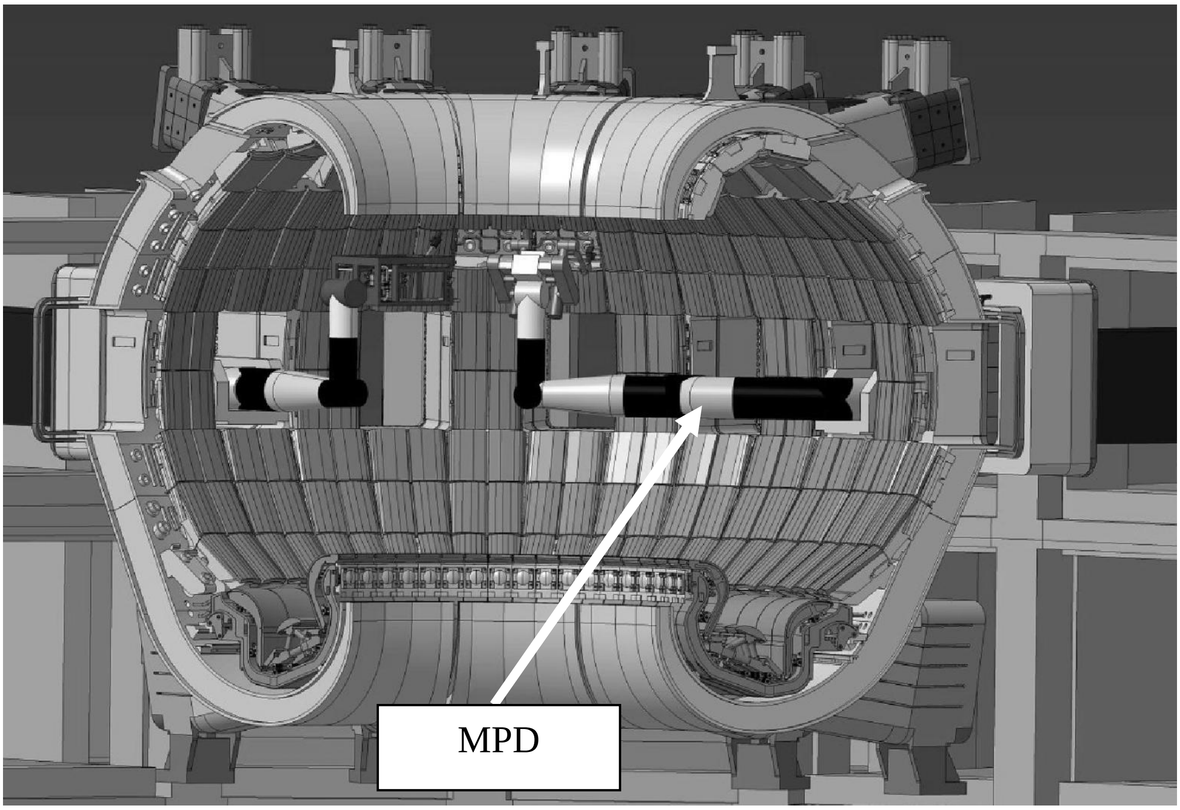


Figure 8: The ITER Multi Purpose Deployer operating inside the ITER torus

1.3.7 Divertor Maintenance

The ITER Divertor comprises of 54 cassettes located in the lower region of the VV (see figure 9) its function is to exhaust helium and plasma impurities and to provide thermal and nuclear shielding to the machine structure. Replacement of the Divertor is expected to be carried out using solely RH methods [Palmer 2005].

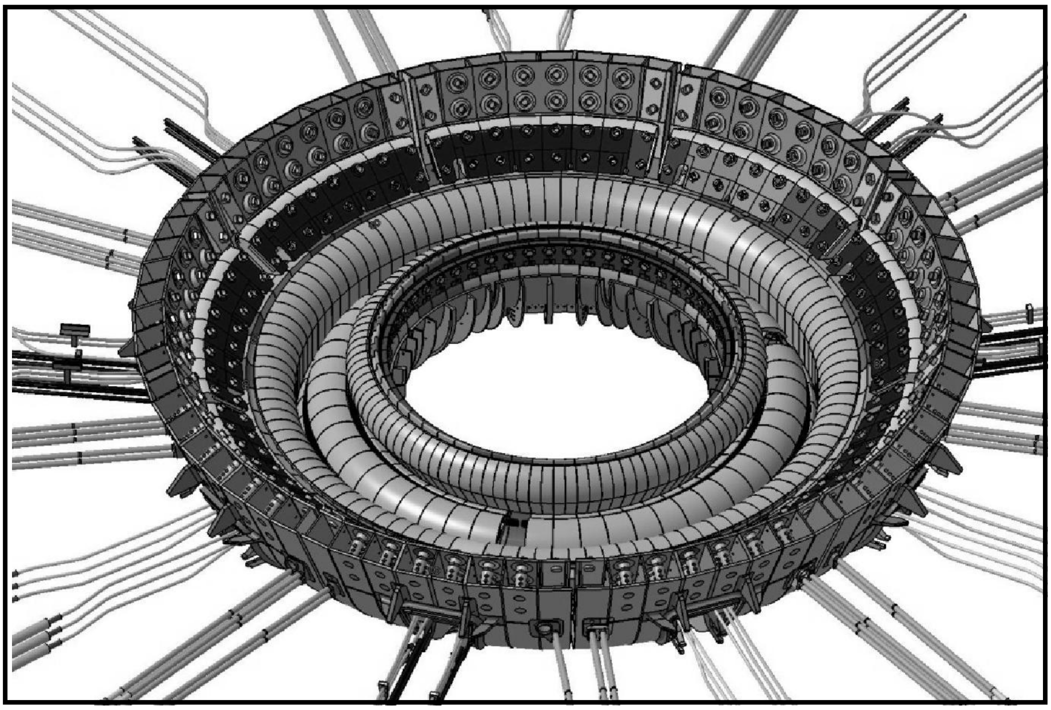


Figure 9: Assembled ITER Divertor

Periodic replacement of the Divertor is necessary due to erosion of Plasma Facing Components (PFC) by neutron bombardment.

1.4 ITER Requirements for Pipe Maintenance

During ITER operation, each Divertor Cassette is connected to 2 water cooling pipes. In order to extract the complete Divertor during shutdown, each of the 108 cooling pipes must be cut using RH deployed cutting tools. The cooling pipe connections are located at the outer wall of the torus where access is severely restricted.

Once the Divertor Cassettes are removed from the torus they are transferred to a Hot Cell for reprocessing, again under RH conditions due to residual secondary activation. To replace eroded PFCs, a further 18 pipe joints for each cassette must be cut and subsequently rejoined in the Hot Cell, again under RH conditions requiring RH pipe cutting and welding *pipe maintenance tools*. The pipe joints in the refurbished cassette are then leak tested prior to replacement in the Torus, requiring a temporary vacuum tolerant seal. Leak tight Divertor Cassettes can then be replaced inside the Torus [ITER 2005], requiring the water pipes to be *re-welded*.

The task of cutting and subsequently re-welding the cooling pipes for the Divertor is complicated by the fact that each cassette presents different locations of cooling pipes. Some cassettes include a diagnostic electrical connector, further limiting tool access.

The RH tools necessary to cut the water cooling pipe between the Divertor and the ITER VV, to re-weld it along with the associated tasks such as inert gas purging necessary to create a non oxidising environment for a properly fused weld and inspection of the weld quality have not yet been finalised. It is these *pipe maintenance tools*, that are the focus point of this research.

Details on environmental conditions for Divertor pipe joints and operating requirements for RH equipment in VV have been outlined [ITER 2005]. Engineering requirements for the pipe joint and tooling is presented in table 2.

Environmental Conditions during RH Divertor pipe maintenance operations	
Temperature	50 ˚C air
Pressure	Atmospheric (0.1 MPa)
Radiation	200 Gy/hr
Atmosphere	Dry air
Operating Requirements for Divertor Pipe Joint	
Pressure	Cassette Inlet 4.2 MPa Cassette outlet 2.38 MPa
Temperature	Coolant Inlet temperature = 100 °C Coolant Outlet temperature = 152 °C Bake out temperature = 240 °C
Criteria for leak test	10^{-9} Pa·m^3·sec^{-1}
Neutron loading	0.5 W/cm^2

Nominal cooling pipe dimensions	Wall thickness = 5.16 Outer Diameter (OD) = 73.03 Inner Diameter (ID) = 62.71
Pipe alignment forces	Alignment in axial direction = 1000 N Alignment in radial direction = 500 N

Table 2: Extract of ITER Divertor RH pipe maintenance engineering requirements [ITER 2005]

The selection of materials and for RH equipment working in the Divertor region is strictly limited to the advice given in the ITER organisation design guides such as the Vacuum Design Handbook [ITER 2001] and applicable reactor construction code such as RCC-MRx [RCC-MR 2007]. Structural materials used for RH equipment must be either AISI 316 Stainless Steel or anodised aluminium alloys. Materials containing halogens (F, Cl, Br, and I) are strictly prohibited as they can poison the plasma and inhibit fusion reactions. Finished equipment must be assembled and cleaned to vacuum quality clean conditions, to minimise contamination and facilitate the required vacuum level. Clearly no paint, or surface coatings are allowed due to potentially high temperatures and contamination risk.

1.5 The Challenges of Remote Pipe Maintenance at ITER

The challenges associated with performing remote pipe maintenance on ITER type applications represent the basis for this research. The task of pipe maintenance on the ITER Divertor has presented RH engineers with some significant technical challenges. Welding and cutting are well established industrialised techniques and represent an obvious candidate solution [Rolfe 1999]. Where welding and cutting are commonly practiced in the absence of human intervention such as automated production type environments, parameters such as tool access, joint geometry, weld power and metallurgy can be precisely controlled. The complexity of the ITER machine means that a similar degree of control cannot necessarily be achieved.

1.5.1 The Joint European Torus

Those involved in the development campaign have looked to the experience gained at the Joint European Torus (JET). JET is a magnetic confinement fusion machine or tokamak based at Culham south of Oxford in the UK. JET is the largest and most powerful tokamak currently operating, its purpose being to study plasma physics paving the way for fusion power reactors, see figure 2. The JET torus has a major and minor radius of 3 m and 1.25 m giving a plasma volume of 155 m^3. This compares with the ITER's, major and minor radii of 6.2 m and 2 m, plasma volume of 837 m^3. JET is the only experimental fusion machine with an RH facility capable of performing fully remote operations [Rolfe 2007]. Since 1998 more than 7000 hours of remote operations have been performed at JET, covering over 450 different types of Remote Handling task. A large suite of RH equipment including two ten metre articulated booms (see figure 10), servo-manipulators and a range of tooling is regularly used to make major changes to the JET machine configuration, see figure 11. The system of two booms at JET allows the servo-manipulator and tool, component transfer module to work in parallel, increasing the efficiency of operations.

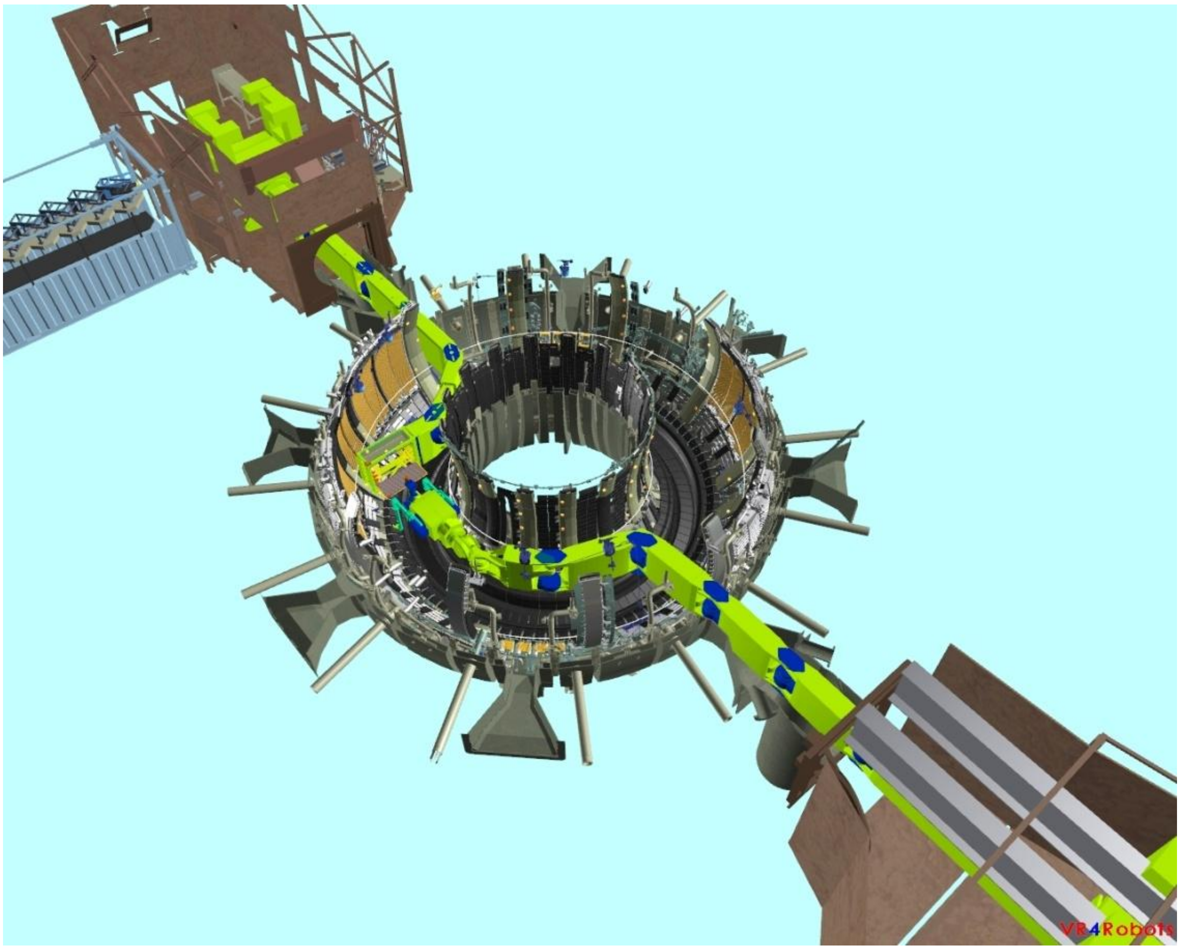


Figure 10: VR image of both 10 m articulated booms used at JET

Comparable jointing problems were encountered on the JET machine as part of a water cooling circuit inside the JET VV. RH engineers at JET solved these problems by using a conservative approach to design, simplifying the process where possible within the limitations of the task. This resulted in a situation where simple single pass autogenous welds could be made on thin walled pipes with flexible bellows to ease alignment and joint fit-up. Brief manual intervention was permitted in exceptional circumstances at JET greatly assisting some of the remote welding and cutting tasks, although the fundamental philosophy behind the RH facility was to minimise human exposure to hazardous radioactive environments.

A direct extrapolation of the successful results gained at JET to the jointing requirements of ITER cannot necessarily be made due to the more stringent conditions on the ITER machine. Tool access will be severely restricted complicating tool placement as well as task viewing and recovery from failure. Due to the levels of activation the use of cameras will be limited. Significantly, large diameter pipe sizes with large wall thicknesses are being considered for Divertor cooling, consequently little compliance will be available seriously complicating joint fit-up prior to re-welding [ANSALDO 2004].

Figure 11: The Mascot manipulator inside the Joint European Torus removing a Divertor assembly using chest mounted winch, special Remote Handling compatible bolting tool and specially designed lifting jigs

The JET experience also illuminated some fundamental drawbacks and operational risks associated with cutting and welding principals. Central to these is the unavoidable need to perform cutting using material removal techniques. Processes such as orbital lathe cutting and sawing are highly energetic and can result in cutting tip jamming/failure and distortion to the remaining pipe stubs. Mechanical cutting also removes material from the piece parts which has to be accommodated somehow in the refurbishment. Re-welding must also be performed outside the Heat Affected Zone (HAZ) of the previous weld. This consumption of the pipe length means that the number of successive re-welds is therefore limited for a given component. There is also the added risk of contamination of the VV by cutting debris [Shuff 2009].

Cutting and welding also require a large tool inventory consisting of relatively sophisticated mechanical tooling with many moving parts. Numerous refurbishment tools were required at JET such as jacking tools for restoration of pipe circularity, de-burring tools for machining frayed edges on pipe stubs and bevelling tools for improved weld penetration. Each of these operations required some form of metrology to confirm their successful completion, often backed up with a manual (human) visual/tactile verification. The increased demands of the ITER machine will only serve to magnify the underlying issues of the weld/cut approach [Shuff 2009].

All of the issues discussed here bring into question the practicality of welding/cutting for pipe maintenance at ITER. The objective of this work is to create a more conservative pipe jointing strategy. The principal criterion for the solution is that mechanical cutting be avoided along with the associated task complexity. The solution also has to meet the requirements for use on the ITER machine such as UHV tolerance and structural qualities approaching that of a welded joint.

1.6 Objective of the Research

The objective of this research was to develop a high strength UHV pipe jointing technique for ITER type applications that can be remotely assembled and disassembled. The joint was required to have structural qualities approaching that of a weld but with the crucial benefit of not requiring a destructive mechanical cut to break the joint.

The driving factor for the research was to develop a solution that overcame the limitations found in the current state of the art in RH pipe joining - outlined in the introduction of this work - providing a low risk, conservative, easy-to-use pipe jointing method.

1.7 Structure of Thesis

The structure of the thesis roughly reflects the generic product development life cycle:

CHAPTER 1: INTRODUCTION: The technical challenges of pipe jointing found today in the field of Remote Handling for fusion are outlined.

CHAPTER 2: STATE OF THE ART: A literature search or State of the art review is presented, defining what technology is currently available in the field of Remote Handling to solve the problems outlined in the introduction. The section concludes by defining the limitations of the available technology and the opportunities for development. Having digested the technological challenges of RH pipe jointing for ITER and the deficiencies in the available solutions (state of the art) a statement of research intent is made, clearly indicating the direction and goals of the work in section *1.6 Objective of the Research.*

CHAPTER 3: A review of diverse alternative pipe jointing techniques is presented. The chapter concludes with an evaluation of the techniques studied and the selection of the most promising research domain, *brazing*.

CHAPTER 4: The development of the necessary theory for a pipe jointing system incorporating an exotic brazing technique is outlined here. A suitable brazing formula a joint geometry is defined. The theory for a novel approach to structural reinforcement of the brazed pipe joint is presented.

CHAPTER 5: The re-braze pipe jointing technique is then compared to the current state of the art *welding and cutting* in the context of RH operations. With careful reference to the operational experience at JET, task plans are outlined for both brazing and weld/cut approaches, the operational advantages and drawbacks of both techniques are then discussed.

CHAPTER 6: Having developed the brazed pipe jointing theory and demonstrated its operational benefits, a trial of experimentation to validate the braze theory in terms of reversibility, leak tightness and structural quality is reported.

CHAPTER 7: DISCUSSION: The results are summarised and considered in the context of ITER type RH operations. Deficiencies in the experimentation are detailed and future work is outlined.

CHAPTER 8: CONCLUSIONS: The principal achievements of the thesis are presented and their context in the field and significance is stated.

2 STATE OF THE ART REMOTE HANDLING PIPE MAINTENANCE TOOLING FOR FUSION

In this chapter a State of the art literature review is presented, defining what technology is currently available in the field of Remote Handling to solve the problems outlined in the introduction. The section concludes by defining the limitations of the available technology and the opportunities for further development.

As we have seen in section 1.3.7, the water cooling pipes between the Divertor Cassettes and the VV must be cut and subsequently re-welded allowing the cassette to be removed and the replacement reinstalled.

This presents the Remote Handling engineer with a number of potential strategies for how to approach the cutting, welding and related tasks *or pipe maintenance*:

- Strategy 1: Cutting and welding performed from *outside* the pipe, alignment and inert gas purging done from *inside* the pipe.
- Strategy 2: Cutting and welding performed form *inside* the pipe, alignment and inert gas purging done form *outside* the pipe.
- Strategy 3: Cutting, welding and alignment performed from *outside* the pipe, gas purging done form *inside* the pipe.
- Strategy 4: Cutting, welding, alignment and gas purging done from *inside* the pipe.

Tooling operating outside the pipe is deployed using a servo-manipulator, typically the tool is engaged on mounting features on pipe. Tooling operating inside the pipe is deployed from a glove box outside the reactor bioshield.

In the following section a range of solutions following the types of strategies outlined in the above are presented. The designs and R&D results presented in the following section represent the state of the art for RH pipe maintenance.

In the established state of the art for pipe maintenance at ITER described in the following includes only the tools necessary to do the basic ***alignment, cut, weld*** and *(weld)* ***inspection*** operations. These tools are the focus of the state of the art. However, careful reference to the literature and return of experience from JET [Mills 1987], [Mills 1991] shows that to ensure the highest quality joints, additional tools are necessary such as metrology and jacking tools. These additional tools are referred to when discussing deficiencies in the state of the art and when making comparisons between the state of the art and the new methods developed in this work.

RH pipe maintenance will be necessary in a range of environments on the ITER machine, including in-vessel, around the vessel and in the Hot Cell. The most challenging environment, from an irradiation perspective as well as difficult tool access is the ITER Divertor. This pipe jointing scenario is a useful ‘benchmark’ for the development of the tooling and jointing techniques of this research. The capability to work successfully in this environment would ensure the widest possible applicability in other areas of the ITER plant and indeed other high energy physics machines and potentially completely diverse markets.

The following section therefore is focussed on state of the art for pipe maintenance in the Divertor region, as stated the most challenging application. This is an accurate reflection of the approach taken by the ITER organisation, where development work on the Divertor pipe tooling will inform other applications, such as water cooling pipe maintenance on the Neutral Beam system.

2.1 ITER RH pipe maintenance R&D

Considerable work has been performed on the subject of RH pipe joint maintenance at ITER. Due to space constraints on the ITER machine, bore tool systems (BTS) for Divertor pipe maintenance have been investigated. BTS are deployed from an access point outside the machine bio-shield and operate from inside the pipe, welding and weld inspection functions are performed using internal work modules controlled via umbilical.

2.1.1 160 mm Straight Pipe Bore Tool System

Until 1998, the ITER design specified 160 mm diameter straight pipes for Divertor cooling. A BTS (see figure 12) was developed to this specification at the Divertor Test Platform (DTP), Brasimone in Italy [Friconneau 2001]. Cutting, welding and weld inspection operations were performed using separate tool heads, deployed independently *as per strategy 4*.

Figure 12: 160 mm Bore Tool System

Cutting was performed using a milling tool for the first 80 % of the cut allowing swarf to be removed prior to breaking through the pipe wall. The remainder of the cut was carried out using a swage-cutter, swarf free. In preparation for welding, the pipes were brought together using an internal pipe alignment function with pulling capacity of 300 kg. Automatic, continuous multi-pass Tungsten Inert Gas (TIG) welding was used to rejoin the pipes. Data regarding weld quality was generated using Ultra Sonic (US) technology with dedicated processing system. Initial development indicated that the proposed BTS would offer a viable solution for the maintenance of the ITER Divertor.

2.1.2 100 mm Bent Pipes Bore Tool System

Changes to the ITER design after 1998 resulted in a re-specification of the Divertor cooling pipes to 100 mm Ø with the addition of ≥400 mm path radius.

Figure 13: 100 mm Bore Tool System

A novel BTS carrier concept (see figure 13), incorporating cutting, welding, alignment and purging from inside the pipe in a single work module *as per strategy 4,* was developed to demonstrate the feasibility of pipe maintenance under the new constraints [David 2003]. The carrier design can switch between an articulated mode during transit through pipes and a rigid mode when the work area is reached. Alternation between each mode is effected by operating cables arranged so that an applied pulling force reduces the space between the modules creating a mate between module surfaces.

Movement through the pipe is achieved using a flexible fibreglass pushrod. Like its predecessor, pipe cutting is performed using a milling tool for the initial 2/3 cut and a swaging tool to complete the operation. A pipe alignment function was used to slowly release the pipe stresses after final cutting and to bring pipe ends together prior to welding. Joining was achieved using a TIG tack-welding tool and finished with a TIG butt-welding tool equipped with camera to monitor weld quality. Final weld inspection was done using ultrasonic technology.

Tool axial positioning accuracy of ±3 mm was observed for 8 m rod length. Clamping forces of 3 kN were attained with a resultant tool position error of $\leq$0.3 mm. TIG welding was satisfactory in work-bench tests, but was not tested after integration with carrier. The total time to complete the full series of cut-weld-inspect operations was 42 min.

YAG (Yttrium Aluminium Garnet) laser was investigated as a potential alternative cutting/welding technology and possible upgrade for the 100 mm bent pipe BTS.

2.2 ITER Reference Design for RH Pipe Maintenance

Further evolution of the ITER design included again a re-specification of Divertor cooling pipes to 63 mm internal diameter, rendering all previous BTS tooling obsolete.

The current ITER reference design for Divertor cooling pipe maintenance is based on *strategy 1* as described at the beginning of chapter 2. Again welding and cutting is the jointing technology, welding and cutting tools are deployed by a servo-manipulator mounted on the Divertor Cassette movers, either the Cassette Multifunctional Mover (CMM) or the Cassette Toroidal Mover (CTM). The CMM and CTM are Remote Handling movers for installing/removing and transporting the Divertor Cassettes to and from the VV, see figure 14 and 15. See section 5.3 for a full description of the Divertor pipe maintenance procedure. The combined use of the CTM and CMM for both Divertor removal/installation and cooling pipe maintenance has resulted in the working name of ‘Cooperative’ maintenance scheme [Friconneau 2005]. The Cooperative Maintenance Scheme approach is the reference design for ITER RH Divertor pipe maintenance.

Section 5.3 gives a fuller description of the pipe maintenance procedure from an operational perspective, including the functions of the CMM and CTM. This section deals first with the jointing technology and tools involved.

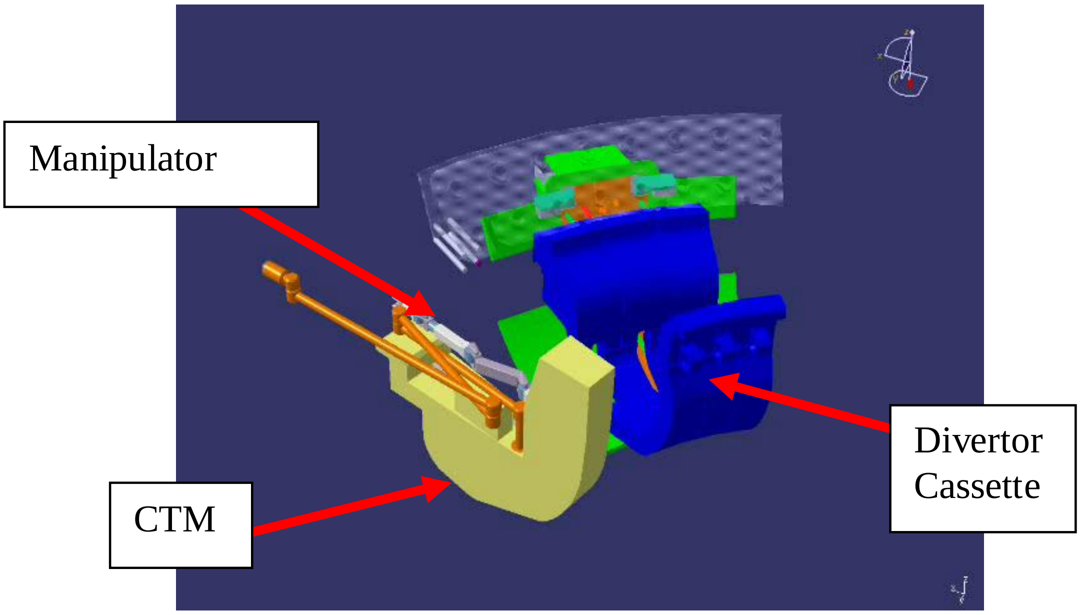


Figure 14: General Layout for Cooperative Pipe Maintenance Scheme

Figure 15 shows the servo-manipulator mounted on the CMM performing pipe welding on the Divertor Cassette cooling pipes as part of the cassette re-installation. Cutting tools are deployed in the same way.

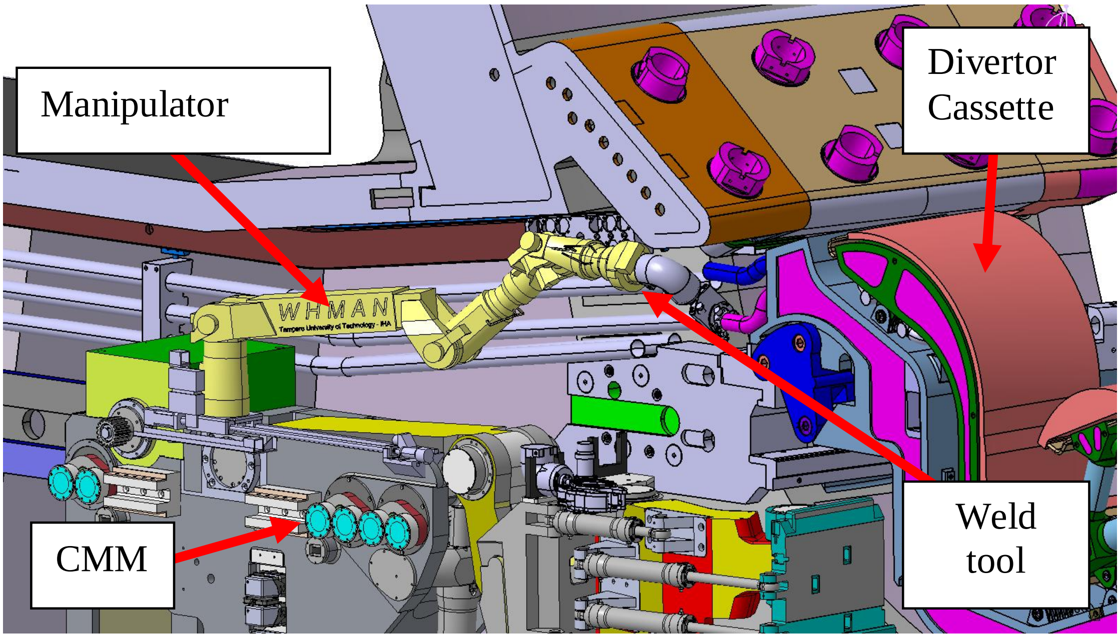


Figure 15: CMM mounted manipulator deploying welding tool to Divertor Cassette cooling pipe

Figure 16 shows the servo-manipulator in the storage position, with tools also stored.

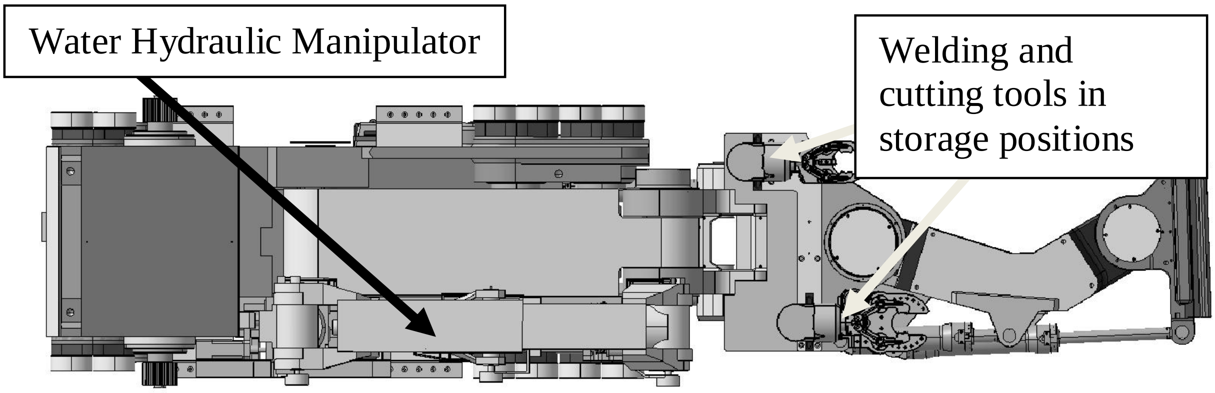


Figure 16: CMM showing pipe maintenance tool storage positions

2.2.1 ITER Reference Design Pipe Maintenance Tools

Due to lack of availability on the commercial market, a dedicated pipe alignment tool concept has been outlined for the ITER reference design, *Cooperative Pipe Maintenance scheme,* figure 17.

Figure 17: Cooperative Pipe Maintenance Scheme alignment tool

The alignment tool is placed into the cooling pipe at the glove box outside the ITER bio shield and positioned at the pipe join area. Alignment forces are generated by mechanical screws driven by flexible drive shafts of 15 m length, operated at the glove box outside the machine bio-shield. The tool is primarily composed of two articulating sections, each section has three fingers extended via the mechanical screws. Once the fingers are clamped against the inside of the pipe, the articulating sections can be drawn together, again using the mechanical screw, in turn bringing the pipe ends into abutment. The fingers are retracted using elastomer return springs. Guide wheels shown in figure 17, help the tool translate along the inside of the pipe. Two inflatable seals front and back create a local inert gas chamber at the weld joint when inflated. Axial and radial alignment forces of 2000 N and 5000 N respectively have been calculated for the tool. The concept requires further development to determine its full practicality.

The proposed cutting tool for the ITER reference design is based on the Oxford Technologies Ltd type RCH 150, proven in service at the JET fusion project, see figure 18. A lathe type tool bit is used to affect cutting. Swarf generated is in the chipped form and is removed from the work area using a vacuum line. To date the RCH 150 has only been deployed manually.

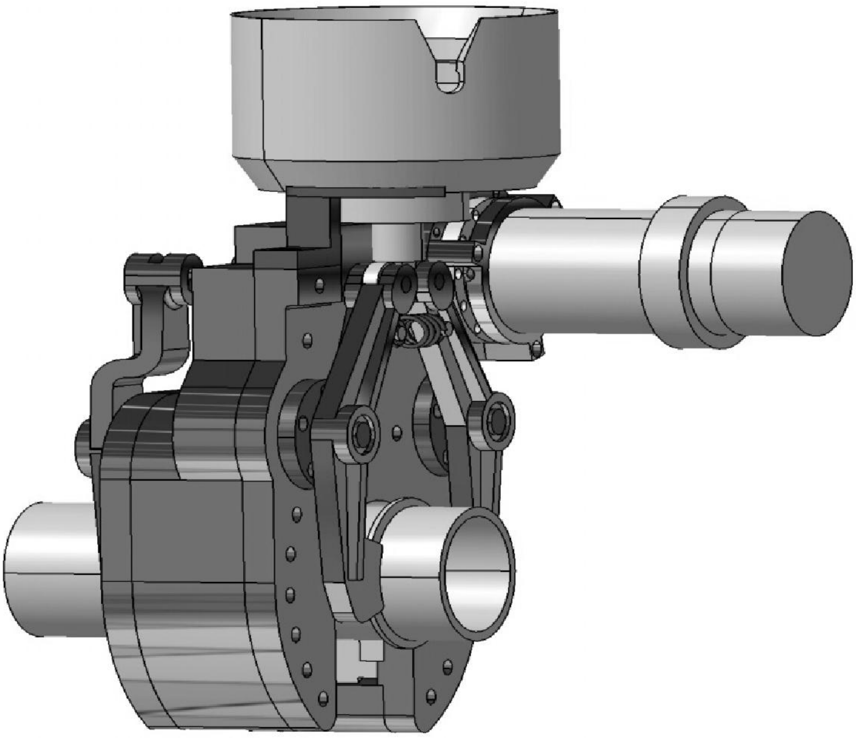


Figure 18: Cooperative Pipe Maintenance Scheme orbital cutting tool

The welding tool detailed for the ITER reference design the system is based on the commercially available Orbitalum Tools GmbH product [Orbitalum 2011]. The tool features automated arc gap monitoring and adjustment, and arc voltage monitoring for for improved weld consistency. For pipes ranging Ø 30 mm to Ø 115 mm the appropriate size for the ITER reference design the tool weight is 20 kg. Integrated wire feeders are an available option. A number of modifications are proposed to adapt the product to the task at ITER, see figure 19. These include additional features in the clamping system to allow the tool to fit to a location ring on the pipe. The tool uses a water cooled, Argon shielded TIG welding head, capable of pipe thickness ≤ 10 mm. The Orbitalum tool was originally developed for manual deployment. A range of similar orbital welding tools are available on the market from various manufacturers, with a variety of clamping arrangements and diameter ranges.

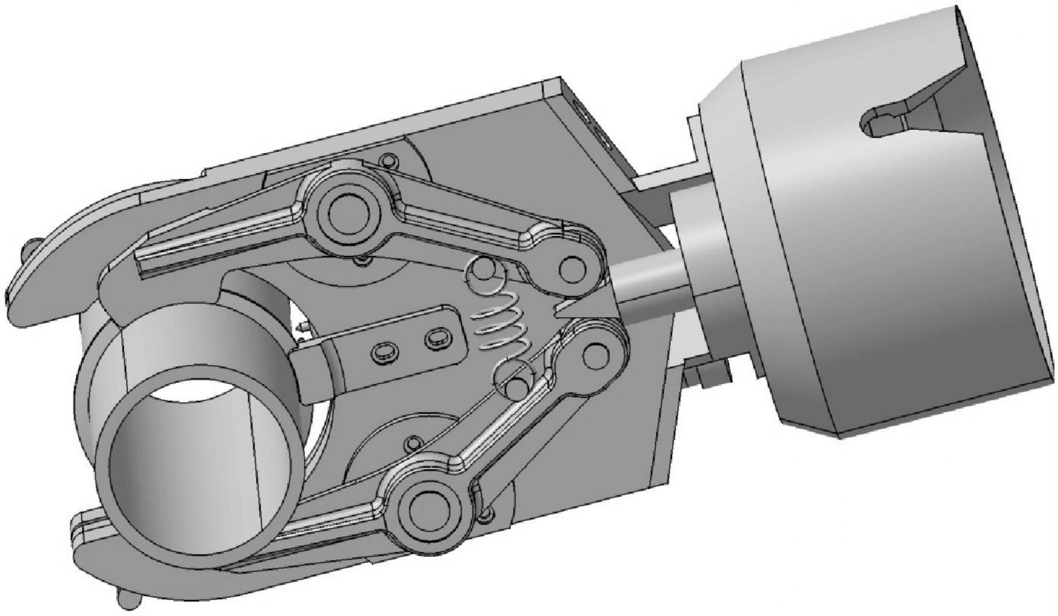


Figure 19: Cooperative Pipe Maintenance Scheme orbital welding tool

Ultrasonic (US) technology has been identified for inspection of weld quality in the ITER reference design, *Cooperative Maintenance Scheme*. The tooling to be used is a re-design of a US probe developed and proven as part of the BTS development programme (see figure 20) like the alignment tool, the US works within the bore of the pipe, inserted and controlled from outside the ITER machine bio-shield. To achieve a usable US signal, a temporary water interface environment is created between the probe and the pipe surface. The probe isolates the pipe section of interest using inflatable seals and the trapped volume is then filled with water. The US signal is created using two arrays of 30 piezoelectric transducers, arranged around the cylindrical surface of the probe. The US signal from the probe is processed and digitised using a computer system away from the insertion point in an RH control area.

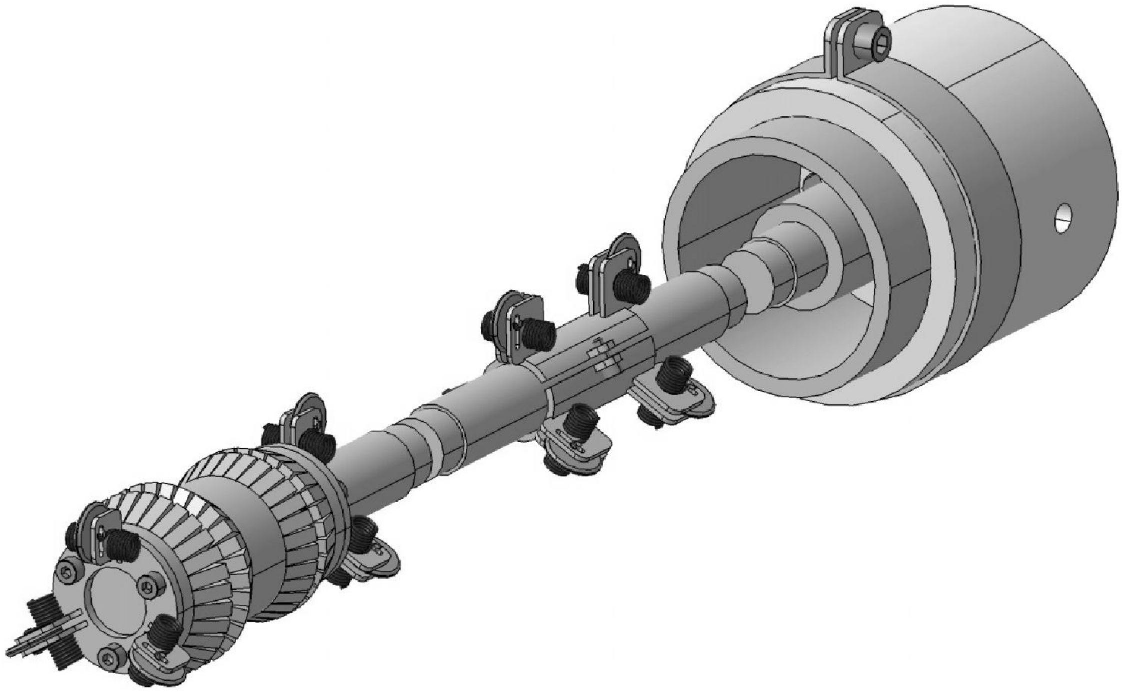


Figure 20: Cooperative Pipe Maintenance Scheme Ultrasonic (U.S.) inspection device

2.2.2 DTP2 Tampere

The maintenance strategy outlined in the cooperative pipe maintenance scheme renders much of the work carried out at DTP in Brasimone obsolete. DTP2 located in Tampere, Finland hosted by Technical Research Centre of Finland (VTT) and Tampere University of Technology (TUT) is a full scale testing platform for Divertor maintenance, including pipe maintenance testing.

The test facility consists of a 27 degree segment of the reactor vessel, Divertor component, CMM transporter, manipulator and various maintenance tools [Palmer 2007], see figure 21.

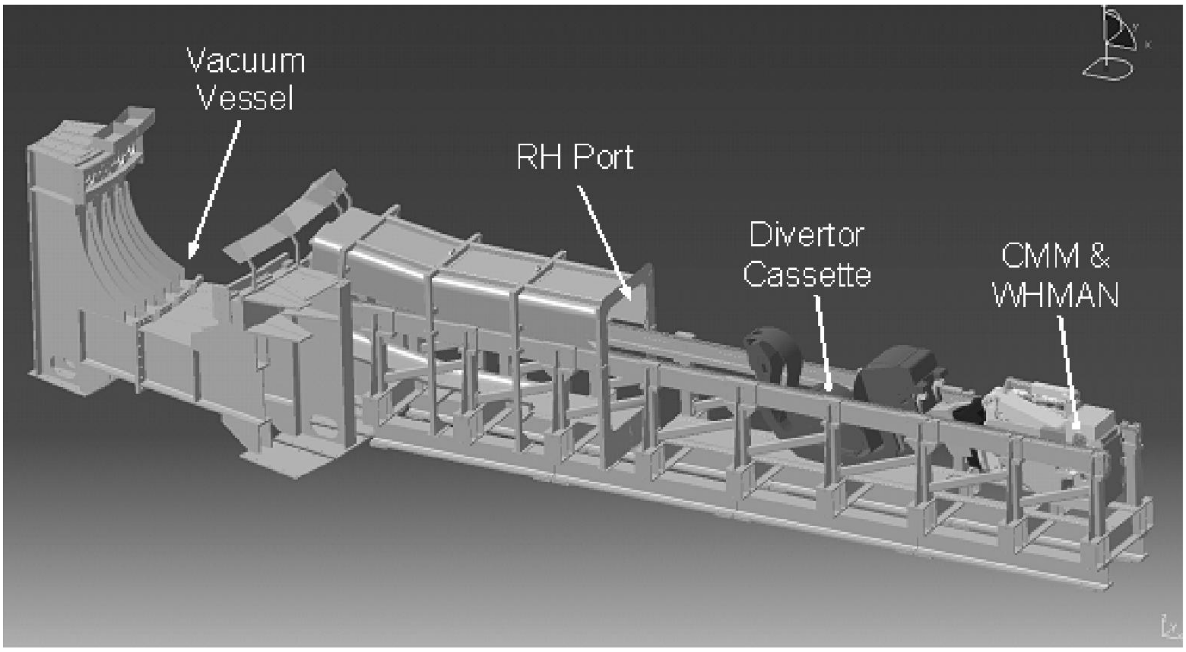


Figure 21: DTP2, Tampere, Finland

The replica Divertor Cassette weighing 9 tons is transported by the mock-up cassette multifunctional mover. Functions such as locking/unlocking of cassette will be performed using a water hydraulic manipulator WHMAN mounted on a rail inside the reactor vessel segment. The WHMAN will be used to deploy all pipe maintenance tooling for use on Divertor Cassettes, see figure 22. Designed by Tampere University of Technology’s Department for Intelligent Hydraulics and Automation (IHA), the objective for the WHMAN is to create a machine that will be 1 MGy in order to meet ITER requirements for radiation hardness. The device will be mounted on the CMM and CMM to assist with Divertor maintenance including pipe maintenance, see figure 23. Water hydraulics are used over oil as oil poses a contamination risk to the ITER vacuum vessel. Hydraulic actuators are compact and powerful giving the manipulator a load capacity of 735 N at full extension. WHMAN features a tool changer allowing the various tools for cassette locking/unlocking, pipe joining/disassembly to be deployed serially in the work area.

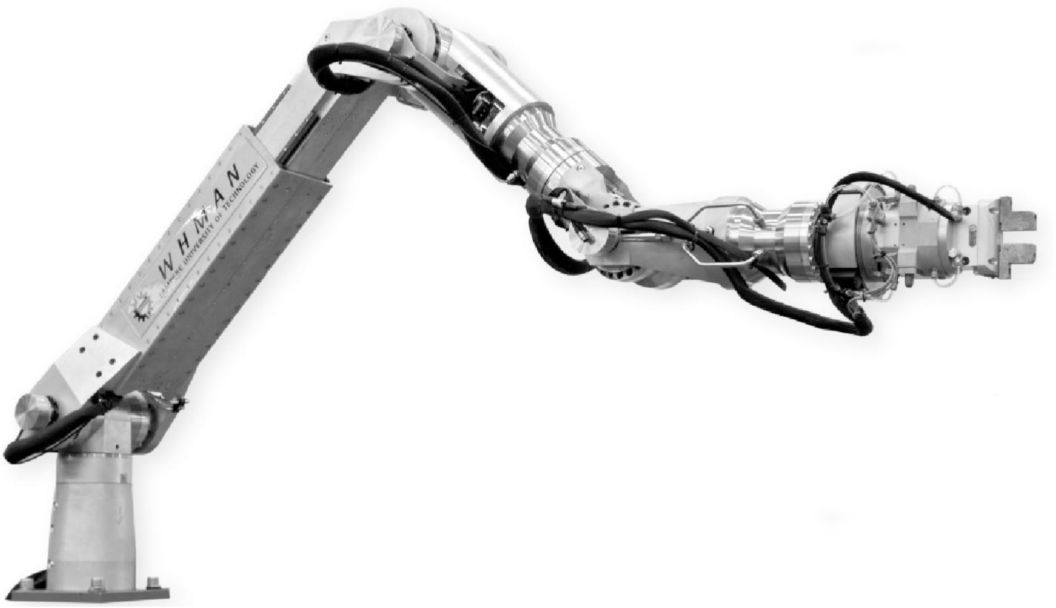


Figure 22: The Water Hydraulic Manipulator for ITER Divertor maintenance, developed by Tampere University of Technology's Department of Intelligent Hydraulics and Automation

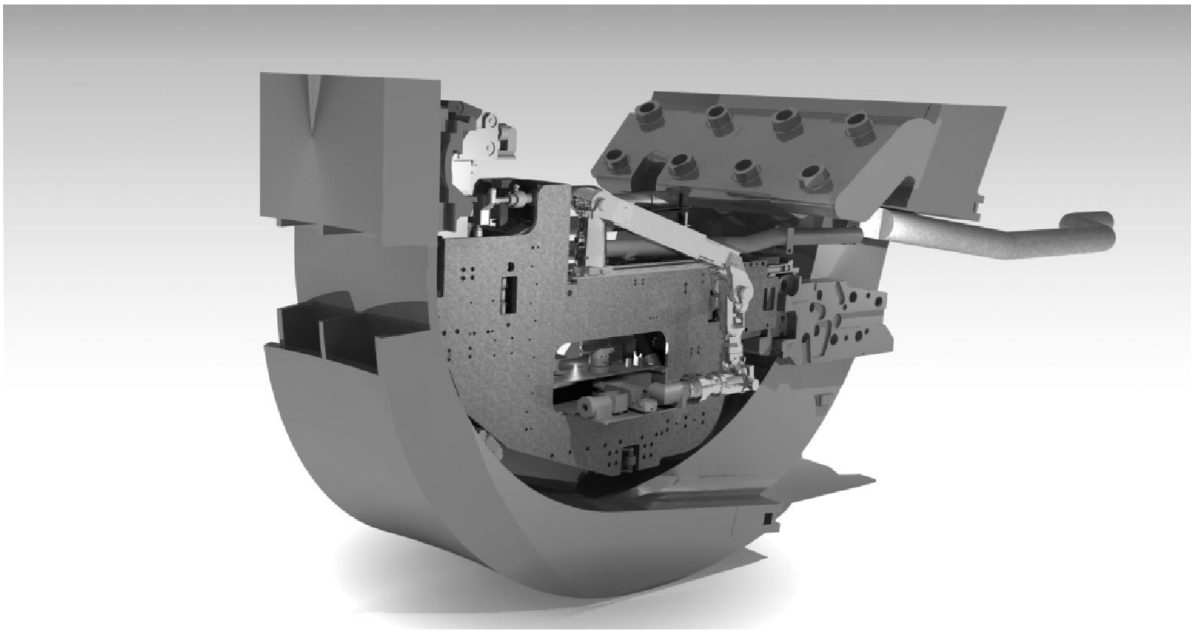


Figure 23: The compact WHMAN mounted on the Cassette Toroidal Mover (CTM), shown exchanging Divertor maintenance tools

Operations at DTP2 are carried out from a mock-up control room, where associated software and HMI's can be tested. [Friconneau 2005].

2.3 Pipe Maintenance at JET

JET is the only experimental fusion machine with an RH facility capable of performing fully remote operations [David 2005]. Welding and cutting operations have been successfully performed on the JET machine. TIG for vacuum quality welds, Metal Inert Gas (MIG) welding for structural quality welds, and orbital cutting have been made using numerous specially designed tools. More than 250 orbital welding and cutting as part of a *pipe maintenance* operation were successfully completed during the installation of a water cooling circuit inside the JET torus. Although the work was performed using tooling that was designed for RH deployment, conditions at the time were such that manned intervention was permitted for short periods.

The cutting and welding RH pipe maintenance tools developed for JET are described in detail along with their applications in the literature, [Mills 1987], [Mills 1991], [Shuff 2009]. A summary of this data is given in the following section. The tools described below were designed for a maximum radiation tolerance of 2.5 Sv/hour. In order to be compatible with the RH servo-manipulator the tools were designed to be lightweight, < 12 kg.

2.3.1 Installation of in-vessel Water Cooling circuit at JET

The installation of a new water cooled belt limiter and Ion Cyclotron Resonance Heating (ICRH) Antennae into the Vacuum Vessel is a good reference example of RH pipe maintenance operations carried out at JET.

The belt limiter comprises of two poloidal rings located above and below the equatorial plane of the vacuum vessel. Each of the two rings features finned water cooling pipes with graphite tiles mounted between the fins. Eight ICRH antennae were installed, each requiring a water cooled electrostatic screen.

The belt limiter cooling pipes and various diagnostics were installed into Ø 91 mm ports within the JET VV, see figure 24. This necessitated the removal of factory fitted blank-plugs from the 55 ports, see figure 24, using an orbital lathe cutting tool, see section 2.3.3. Following the cut, a water hydraulic puller was used to remove the blank. Extraction forces varied and in some cases three times the nominal load was required, resulting in damage to the port structure attached to the vessel.

Unexpected damage such as this is an example of why additional tools such as metrology and geometry restoration tools are necessary when performing pipe maintenance operations.

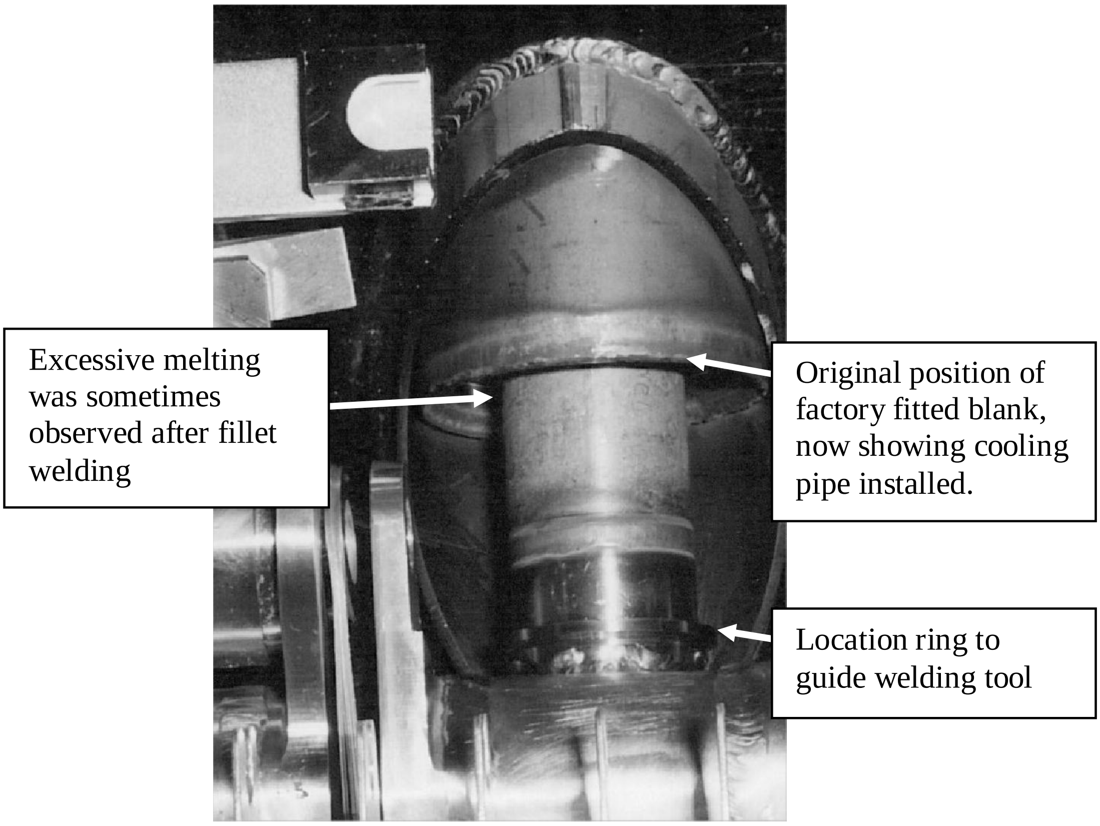


Figure 24: Ø 91 mm ports inside the JET VV

The belt limiter cooling pipes were installed into the port using orbital welding tools, see figure 27 and 28.

The Ø 50 mm orbital welding tool, see figure 27 was positioned and guided by a location ring, see figure 24, and also figure 25. Again things did not always go to plan. Due to manufacturing inconsistencies, excessive melting of the port rim was observed. This necessitated a full visual inspection of each weld, a process that might not necessarily be achievable at ITER, due to restricted access for cameras and the high radiation environment preventing the use of cameras altogether in certain cases.

Bellows manipulation tools were necessary to create the necessary installation clearance, preventing any damage to the pipe ends as the component was brought into position and to provide the necessary control of alignment and abutment (joint fit-up) prior to welding.

The work highlighted the many limitations of RH deployment of pipe maintenance tools, the lack of direct human senses, for viewing of welding arcs, inspection of welds and the use of tactile senses for the placement of tools and confirmation of joint fit-up.

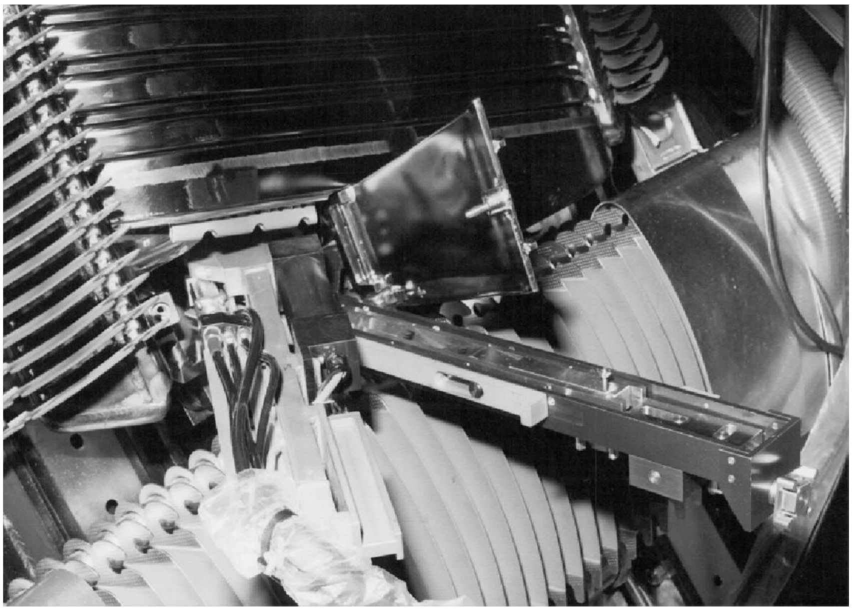


Figure 25: Welding tool (see also figure 27) positioned at the Ø 91 mm port above the belt limiter

Some of the tools used in this and similar pipe maintenance operations are described in the following section.

2.3.2 Welding Tools

The welding tools presented here were used for joining pipes during RH operations on JET.

A compact UHV fillet welding tool was developed for welding sleeve components in areas where access was restricted on the JET VV, see figure 26. TIG weldments with the addition of filler material are made using a water cooled torch, weld power is provided by a unit away from the work area outside the VV.

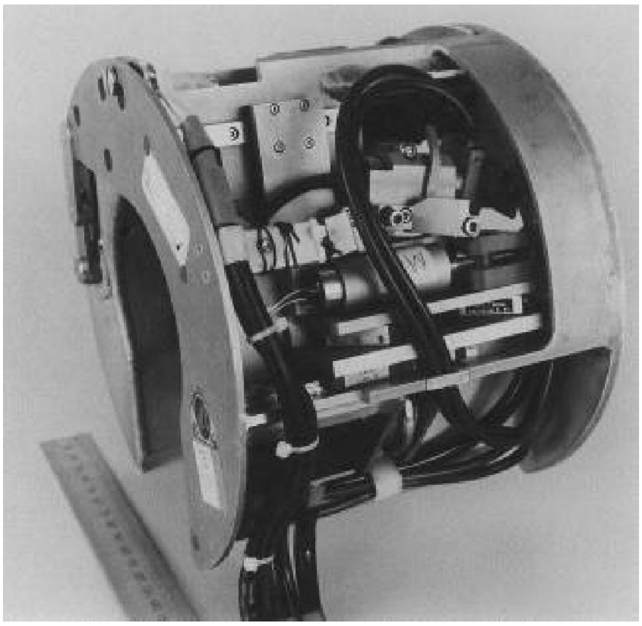


Figure 26: Orbital sleeve fillet welder

An orbital TIG welder was used to join Ø 50 mm water cooling pipes in VV, see figure 27. Insertion rings were used to assist joint fit-up, also aiding tool placement. Tack welds were made followed by a fit-up inspection prior to full single pass autogenous welding.

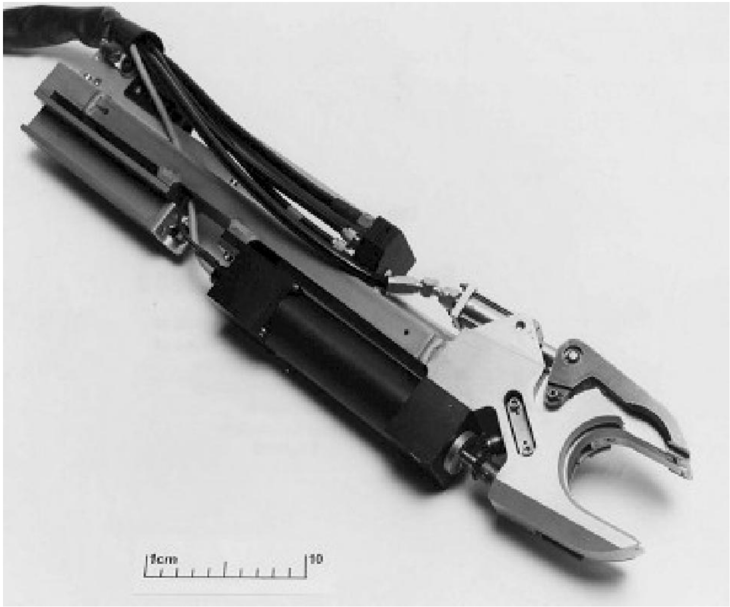


Figure 27: Ø 50 Orbital TIG welder

An orbital BTS fillet welder was also developed for applications at JET, see figure 28. The tool is guided by a location feature on the work-piece, a motorised parallelogram provides automated Arc Voltage Control (AVC) and filler material is provided from a wire feed system.

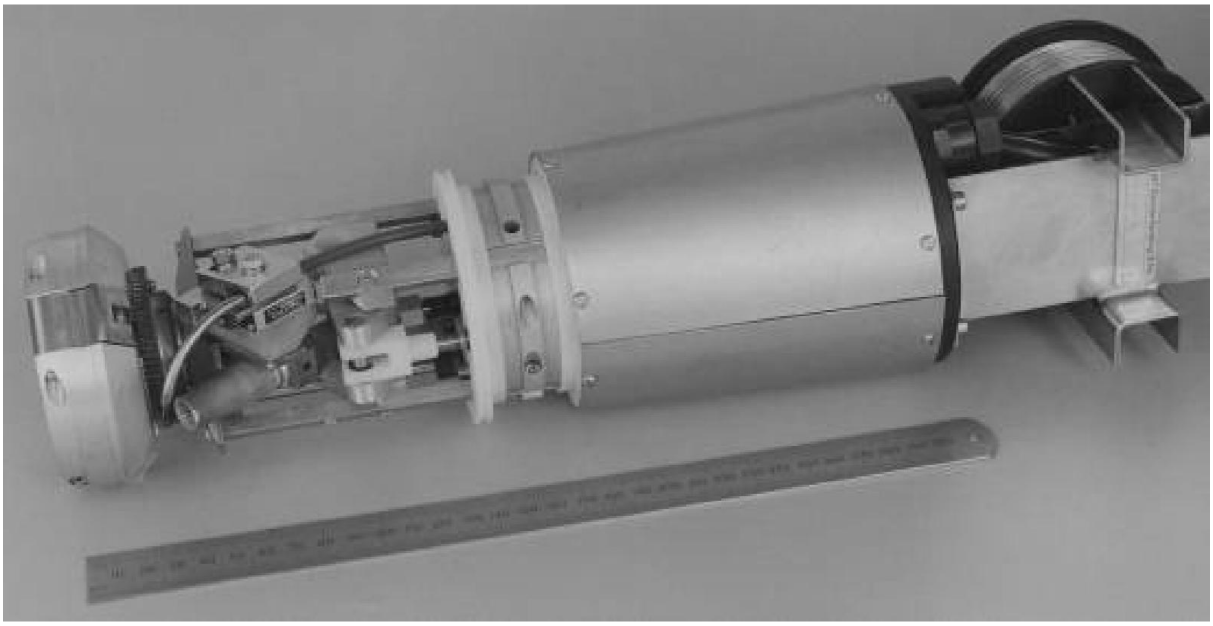


Figure 28: Fillet BTS welder

2.3.3 Cutting Tools

Again, the cutting tools presented here were used during pipe maintenance operations at JET.

A BTS lathe type cutting tool was developed to remove factory fitted blanking plugs in Ø 91 mm ports on the JET VV [Mills 1991]. Low cutting speeds and feed rates were used, minimising tool power requirements and tool weight. Tool clamping was made using 3 water hydraulically powered fingers. Cut-off material was yielded in the chipped form and extracted using a vacuum system. Cutting was driven by an electric motor controlled to provide cutting at a constant preset-able speed of 0.15 – 0.2 m/sec. At this speed no lubricant is required, cut off material is in the chipped form and power requirements are low helping minimise the overall tool weight.

An orbital sleeve cutting tool was developed as part of the JET campaign, see figure 29. The tool operates using a clam-shell arrangement allowing placement over continuous pipe runs. A robust mechanical tool feed was used with low cutting feed-rate.

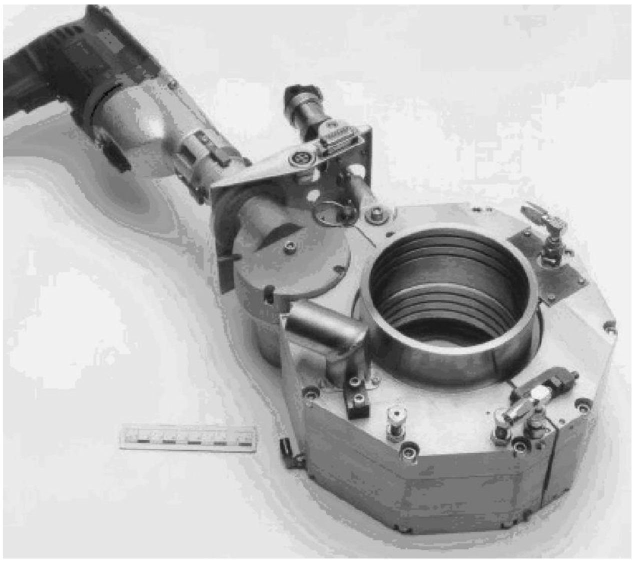


Figure 29: Orbital sleeve cutting tool

A slitting saw tool was developed for cutting pipe runs where tool access was extremely limited. The tool can produce cuts of adequate depth with minimal cutting wheel diameter by eliminating the use of a conventional centre shaft. The tool is driven by internal spur gear teeth and supported by the side faces leaving the outside circumference free to make the cut.

2.3.4 Alignment Tools

Pipe alignment tools were used extensively at JET to position tools and to ensure the necessary joint fit-up prior to pipe welding and also pipe cutting operations.

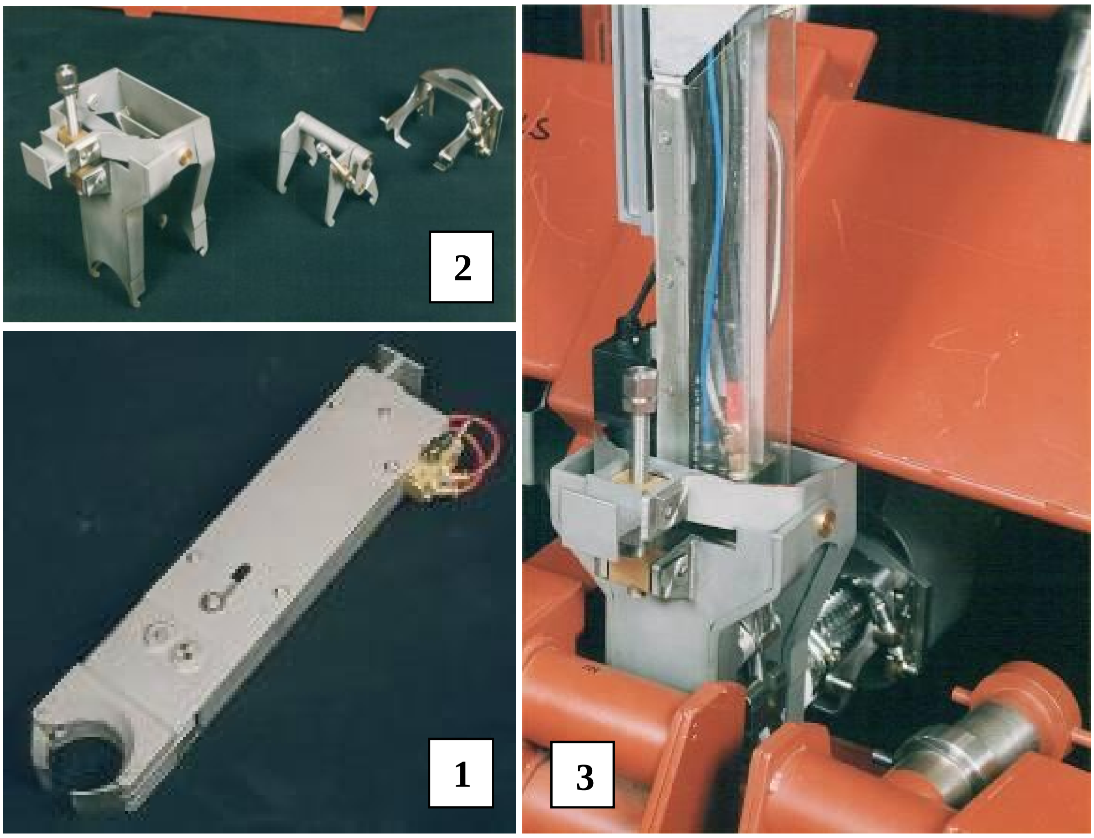


Figure 30: Alignment tools used at JET – 1. Co-axial alignment tool, 2. Clamping tools, 3. Weld tool positioned with joint clamp

Numerous alignment devices were developed for RH welding operations on JET, depending on the nature of the operation, access restrictions and type of alignment required; axial, angular etc, see figure 30.

2.4 Deficiencies in the State of the Art

Problems with the current state of the art with respect to the requirements of ITER have been outlined in the introduction of this work and are explored in the publication [Shuff 2009]. The issues can be summarised as follows:

Alignment Single pass autogenous welding has the lowest risk of failure compared to other forms of welding for UHV pipe work. In order to ensure good reliability for this method the tolerances found to be effective at JET were: abutment + 0.1 mm, co-axial alignment +/- 0.2 mm and angular axial alignment +/- 0.08˚. These tolerances were possible at JET due to the use of thin walled compliant pipes and thin walled bellows.

The same degree of tolerance will prove difficult to achieve on the ITER machine given the use of thick pipes (5-9 mm thickness) and the anticipated prohibition of bellows. Multiple pass welding with filler material can tolerate greater misalignment - up to 0.5 mm abutment - but carries the risk of lack of fusion and voids in the weld seam and as such was found to have a higher failure rate at JET.

Risk of distortion during cutting Various unexpected anomalies were encountered during pipe maintenance operations at JET. These were somewhat mitigated by using thin walled pipes (<1.5 mm). This for example allowed defects in circularity discovered after cutting to be redressed by simple jacking tools. Thicker pipes such as those anticipated for ITER will prove more difficult to manipulate using such tools. Cut edges should ideally be inspected prior to re-welding. Unacceptable finish on the pipe ends will require additional tooling for edge profiling, further complicating the task.

Lost material following cutting Material lost during cutting must somehow be made up in the subsequent re-join. Typically this is solved by utilising some adjustment in bellows. However the use of bellows has been ruled out at ITER for in-vessel systems therefore replacement components must be designed with additional material to bridge the resultant gap. Cut-off material also represents a contamination risk to the VV and must be carefully collected.

Limitation in the number of re-joins Re-welding must be performed outside the Heat Affected Zone (HAZ) of the previous weld, therefore only a limited number of re-welds can be made for a given length of connecting pipe-work.

Large tool inventory Many tools are required for RH pipe maintenance using cutting and welding. The tools covered in the state of the art are the bare minimum necessary for pipe maintenance, careful study of the literature and the return of experience form JET shows additional tools are necessary for tasks such as refurbishment, metrology and bellows manipulation:

- Orbital cutting tool
- Cutting debris extraction device
- Refurbishment tools: de-burring, circularity and bevelling
- Metrology tools: laser/tactile tools to measure in VV stub, to assess pipe fit up; tactile sensors, visual feedback
- Alignment tools
- Bellows manipulation tooling
- NDT tooling: X-ray, ultrasonic, He leak detection.
- Orbital welding tool.

Complex mechanical tools The tools described in the above are relatively complex mechanical systems with many moving parts. Such tools have an appreciable risk of failure compared to solid state devices.

The issues cited at above were found to be problematic at JET; the more stringent demands of ITER in terms of tool access, radiation tolerance and structural integrity will serve to magnify these concerns.

3 REVIEW OF ALTERNATIVE PIPE JOINTING TECHNOLOGIES

In view of the shortcomings in the available RH for fusion type pipe jointing technology explored in chapter 2 state of the art, in this chapter a broad literature search of applicable alternative pipe jointing technologies not based on cutting and welding was performed, with joint reversibility/disassembly as the primary search criterion.

Material joining is a ubiquitous phenomenon, present in most aspects of our daily lives. Brazing, soldering, riveting, swaging, bolting, bonding to give a few examples and their countless incarnations present the Remote Handling engineer with a seemingly broad choice of alternative solutions to *welding and cutting*.

To focus the search for an alternative joining method it is worth revisiting the engineering requirements set out in table 2, summarised here:

- *High strength (comparable to welded joint)*
- *High durability (comparable to welded joint)*
- *Metallic (Stainless Steel) construction*
- *Operating temperature 240 °C*
- *Max Leak rate* 10^{-9} *Pa•m*^{3}*•sec*$^{-1}$
- *Ease of disassembly*

As part of the search for an alternative joining method to *welding and cutting*, diverse industries were considered such as oil & gas and chemical processing. It quickly became clear that the available solutions would be limited to a relatively small domain due to one requirement in particular, the *leak rate*. As we have seen Tokomaks require an ultra-high vacuum to operate effectively, this narrows the available joining technologies considerably. The degree of leak tightness required, 10^{-9} Pa•m^{3}•sec^{-1}, is the equivalent of approximately no more than one droplet of water every 50 years. For most pipe jointing applications this level of stringency is clearly not necessary. To take an example, for swaged type pipe joints encountered in the oil and gas industry as part of this research, half the leak rate stated above would be considered more than necessary.

Much of the material cited in this chapter is therefore drawn from the relatively narrow domain where vacuum systems are to be found such as high energy physics and some industrial applications.

3.1 Shape Memory Alloys

Shape Memory Alloys (SMA) are an exotic material group that undergo spontaneous shape change when subjected to different temperatures. This property has been used create a new joining technique that has had notable success in pipe jointing applications and is therefore of interest to this work. This section introduces the topic of SMAs describing the principals behind their behaviour. Their applicability for pipe joints is explored and finally examples of their consideration for use to create UHV joints in fusion machines is summarised.

The shape memory effect is defined as the capacity of a material to recover a given strain upon stress release and/or heating. At low temperatures SMA materials can accommodate up to 8% strain and will stay deformed until heated whereupon they will return to their original shape.

The discovery of SMA can be traced back to the 1930s when a temperature dependent Martensitic phase was observed. SMAs with useful mechanical properties became available in the 1960s with the emergence of the equiatomic alloy Ni Ti [Buehler 1967].

Since then SMAs have been employed in a variety of industrial applications. The use of SMAs as pipe and tube connectors has been cited as the most commercially successful example of this [Kapgan 1990], [Dunne 2000].

3.1.1 Principles of SMAs

Most commonly SMAs are stressed into a pre-assembly shape, prior to being heated at which point they change shape in the assembled position. SMAs can also be made to exhibit spontaneous shape change on both heating and cooling over multiple cycles. The principles behind this behaviour are explained in the following sections.

3.1.1.1 One Way Shape Memory

The basis for the unique behaviour of Shape Memory Alloys is their ability to exist in two different temperature dependent crystallographic phases, Martensite (M_f) at lower temperatures and Austenite (A_f) at higher temperatures. The higher temperature A_f phase is characterised by a cubic crystalline structure whereas the lower temperature M_f phase is characterised by a rhombic structure [Otsuka 1998]. Upon cooling from the A_f phase shown in figure 31, 1a, M_f is formed with an even distribution of rhombic crystal layer orientations figure 31, 1b. If stressed sufficiently in the M_f phase, shape change is accommodated by a process referred to as *twinning.* During twinning, atoms inhabiting each M_f layer are simultaneously rearranged resulting in a biased distribution of rhombic crystalline orientations, figure 31, 1c. Upon heating the M_f phase reverts to the A_f cubic crystallographic structure which can accommodate only one orientation resulting in the recovery of the original shape.

3.1.1.2 Two Way Shape Memory

Two-way shape memory is characterised by a spontaneous shape change on both heating and cooling. The two-way shape memory effect can be observed in the same materials as those used for one way shape memory but with the addition of a *training regime.* Various training regimes are available; each involves the application of a load in the A_f and/or M_f phases. One example is to apply load in the M_f phase, then to raise the temperature into the A_f phase while maintaining the load and to repeat this cycle. Training regimes set up internal stresses creating what is referred to as *stress biased* M_f. The internal stresses are sufficient to influence the distribution of the rhombic crystal orientations to favour the desired geometry in the M_f phase.

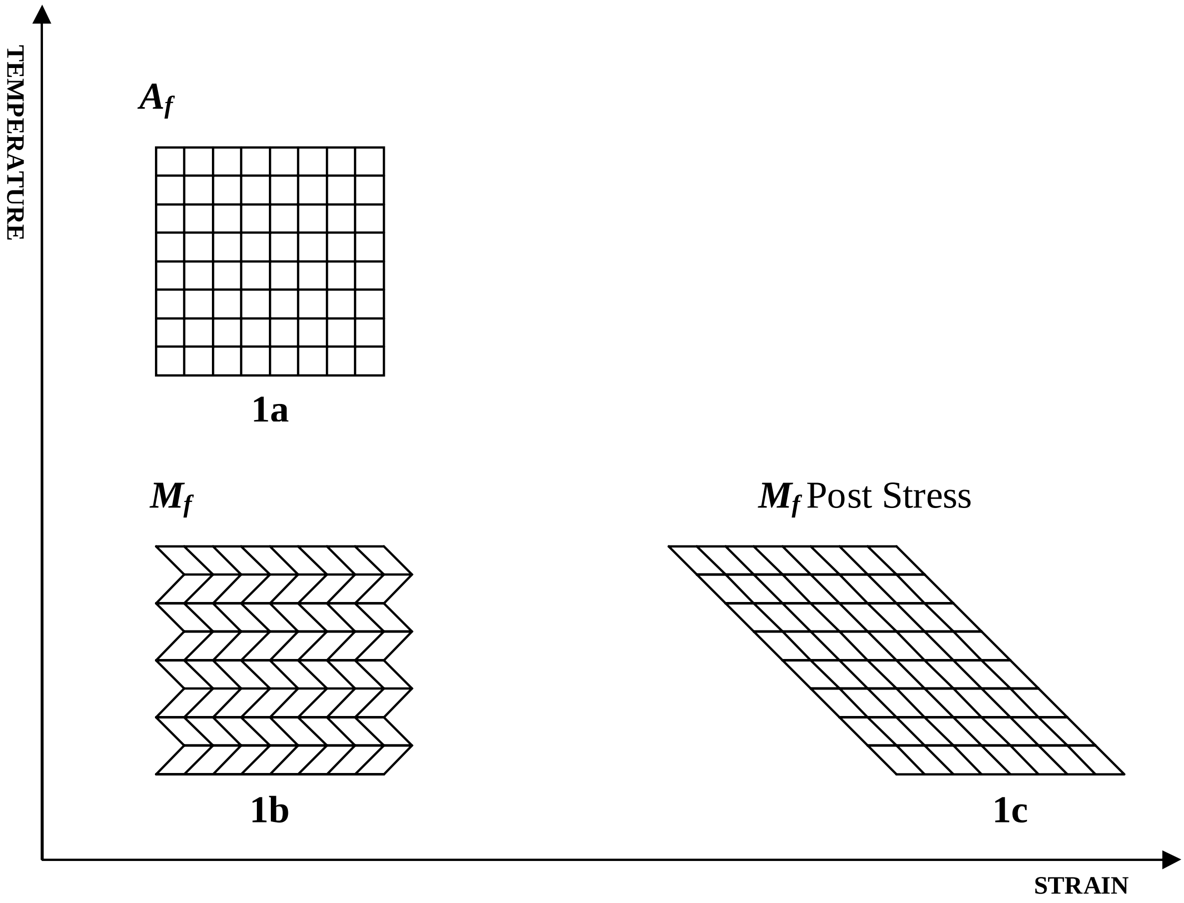


Figure 31: Crystal representation of Martensite and Austenite under different temperature and strain conditions

Some drawbacks are inherent in 2-way shape memory alloy, typically reversible strain is limited to 2% and an upper limit on operating temperature must be observed to avoid removing the 2-way behaviour by annealing.

3.1.2 Development of SMA Pipe Connectors

The first large scale application of SMAs was as a pipe coupling used in the hydraulic system in the Grumman F-14 aircraft. The coupling consists of a machined cylinder of Ni-Ti alloy with circumferential sealing lands on the internal surface. The coupling is cooled to the M_f phase and expanded by forcing a tapered mandrel through the fitting. The coupling is then placed over the pipes in the position of the join and allowed to warm, returning to the A_f phase. The coupling partially recovers the induced strain, making contact with the pipes, the remaining un-recovered strain effects a hydraulic joint rated at 20 MPa [Aerofit 2009]. Figure 32 shows the basic architecture of the joint during installation. For the cylindrical pipe coupling the connecting strength is proportional to the amount of constrained recovery, the wall thickness of the part and the Young's modulus of the material as in the following expression:

$$P_c = \frac{E(R_1^2 - R_2^2)\epsilon}{2R_2^2}$$

Equation 2: Connecting strength of SMA pipe fitting

Where P_c is the connecting pressure, E is the Young's modulus R_1 & R_2 are the internal and external diameters of the component and ϵ is the measured strain. Hence, very powerful connecting pressures can be achieved [Dai 2006].

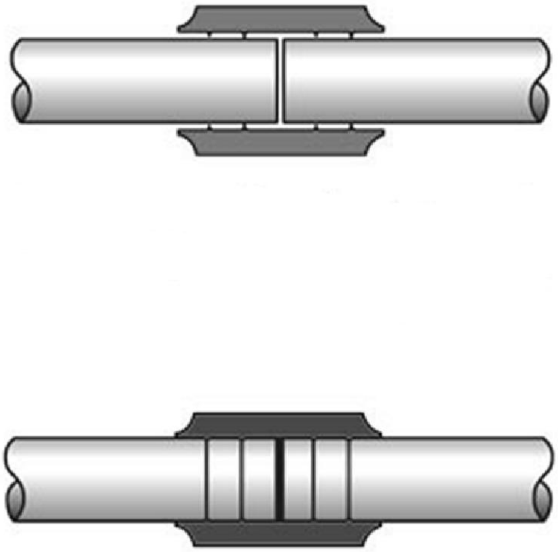


Figure 32: Typical SMA pipe coupling prior to sealing above and post shape change and sealing by swaging below

3.1.3 SMA in Fusion Devices

Proposals for the use of SMAs to simplify RH operations and to speed the replacement process for fusion machine components have been made as far back as 1985 [Nishikawa 1986], [Nishikawa 1988]. With the requirement being for both RH installation and removal, these proposals have focussed on the reversible nature of the 2-way SMA technology. The possibility of using 2-way Ni-Ti to create a vacuum tight seal for in vessel components has been investigated. The study focused on measuring connecting strength, revealing a potential 360 MPa with fully constrained recovery. Reversible strain was again found to be limited to 2 - 3% [Nishikawa 1991]. Larger scale applications of SMAs in fusion devices have been developed such as a vacuum seal connecting a Cassette Compact Toroid Reactor (CCTR) plasma container to a Divertor demonstrating that helium leak rates of 1 x 10^{-9} $Pa{\cdot}m^3{\cdot}s^{-1}$ can be achieved [Nishikawa 1989].

This development activity was followed by investigations into the effects of neutron irradiation on the mechanical properties of SMAs. M_f and A_f transformation temperatures of the Ni-Ti alloy have been seen to shift to lower temperatures following neutron irradiation [Matsukawa 1999]. 2-way Ti-Ni

SMA pipe couplers have also exhibited a 30% reduction in reversible strain following irradiation when heating and cooling [Hoshiya 1998]. Ti-Pd-Cr alloy has shown greater resistance to neutron irradiation and is thought to be a more reliable option for in vessel applications [Hoshiya 1996].

SMAs have also been used as part of a retrofit joint restraint, used to strengthen suspect welded pipe joints in fission power plants [Kornfeldt 1997].

3.2 Mechanical Joints

In this section the use of mechanical joints to solve the research question is considered.

Bolted or mechanically clamped flange type joints using deformable seals are commonly used in vacuum systems. They have the advantage of being easily disassembled and reusable, presenting a seemingly obvious solution to the objective of this research.

Various disconnect-able vacuum flange products are commercially available and many bespoke examples can also be found in the literature. These devices form a vacuum quality joint with the application of a clamping force such as bolting, trapping a sealing medium between two flange faces. The key dimensions for vacuum flanges have been standardised by the International Standards Organisation.

3.2.1 Types of Seal

The various types of seal available for UHV mechanical type joints are presented.

3.2.1.1 Helicoflex® Seal

A circular cross-section seal consisting of a metal wire helix core, inner lining layer and outer sealing layer is available for vacuum flange applications [Lefrancois 1990],[Garlock 2009]. Sold under the trade name Helicoflex, the seal is available in a range of materials. The seal is capable of 1.10^{-9} $Pa{\cdot}m^3{\cdot}sec^{-1}$ leak rate performance and has been used on the TFTR, Tore Supra and JET fusion machines [Mullaney 1983]. The close wound core provides adequate sealing force against flange faces when clamping force is applied. The core provides the added function of accommodating related component creep, bolt relaxation and temperature changes without compromising the quality of the seal, see figure 33. The inner lining provides uniform distribution of spring load against the outer lining. The outer lining is made from a soft metallic material and plastically deforms against the microscopic defects in the flange faces.

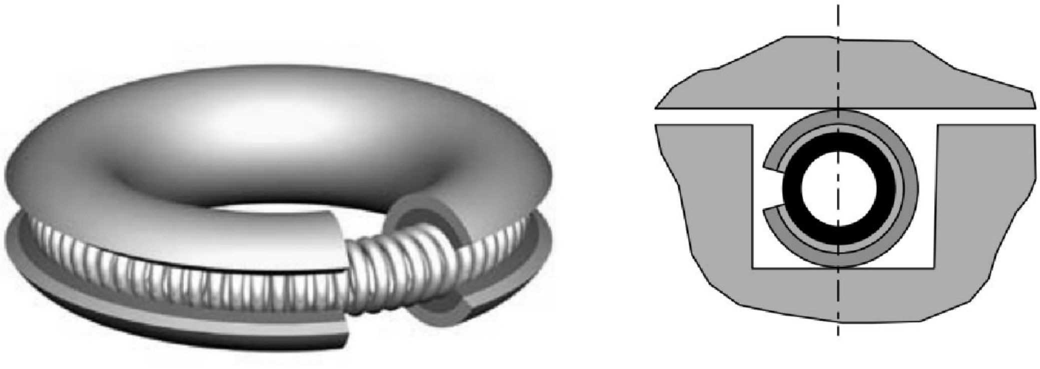


Figure 33: The Helicoflex® seal

3.2.1.2 Conflat System

A flat rectangular cross-section metal gasket used in tandem with a conical knife edge feature in the corresponding flange face is also available for vacuum flange applications [Kurokouchi 2001]. The application of torque to the fixing bolts forces the knife edge in the flange to penetrate the gasket surface. The compressive stress captured between the knife edges affects a vacuum quality seal, see figure 34. The system is vulnerable to leakage if any defect in the flange knife edge should occur. Problems with gasket creep have also been observed under repeated vacuum bake-out conditions [Kurokouchi 2000].

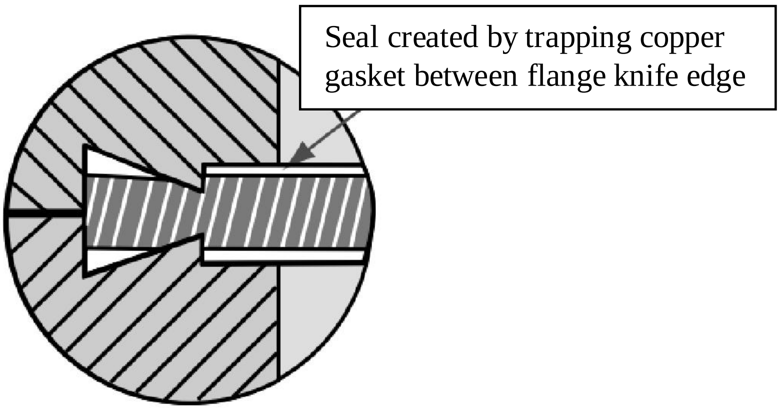


Figure 34: Conflat System

3.2.2 Types of Fastener

Bolting is commonly used to apply the necessary clamping force to create a vacuum flange type joint. Bolting arrangements are usually multiples of 4 evenly spaced around the circumference of the flange face. Gaskets are compressed uniformly by adhering to a bolt tightening sequence. Standards are available for calculating the necessary bolt loading for a particular application [Thompson 2005].

Alternative clamping devices are available for vacuum flange applications that take less time to assemble than the bolted approach. These include double bolt segmented collar clamps, bolted chain clamps for V-band flanges, see figure 35, and roller chain with over centre clamp also for V-band flanges [Mapes 2001]. As discussed previously, a bolted collar clamp has been developed specifically for RH operations.

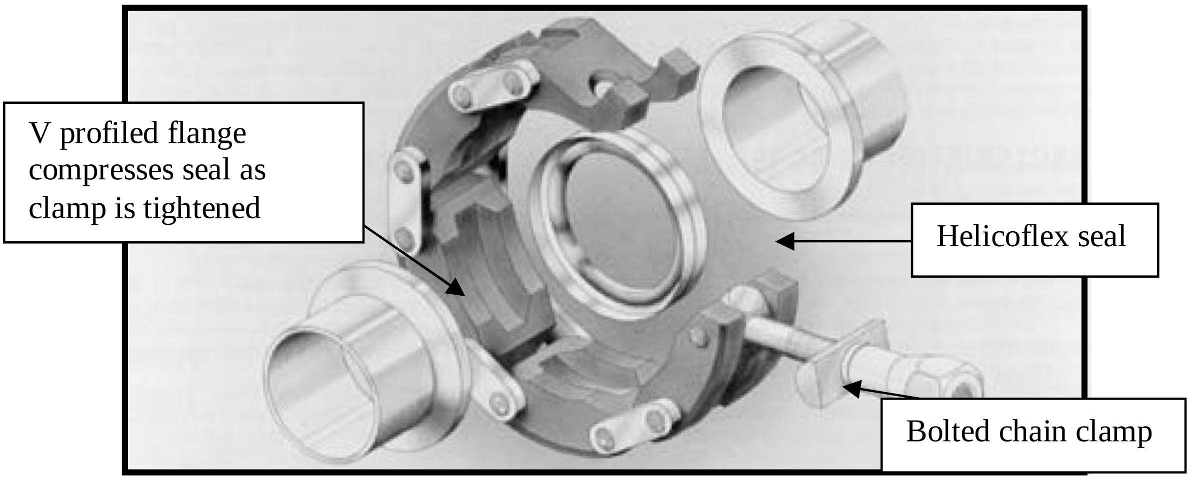


Figure 35: Remote Handling type V-band flange with bolted chain clamp

3.2.3 Swagelok®

The Swagelok tube fitting is used in the power generation industry and at JET (ex-vessel applications) to create UHV pipe joints. To create a joint the Swagelok fitting is positioned over the pipe end and tightened, forcing a pair of internal ferrules to interface with the pipe surface creating a strong grip and seal, see figure 35. Pipe ends with Swagelok fittings attached can then be bolted together to form a vacuum tolerant joint. Swagelok fittings are single use and fresh pipe length must be used for each new joint.

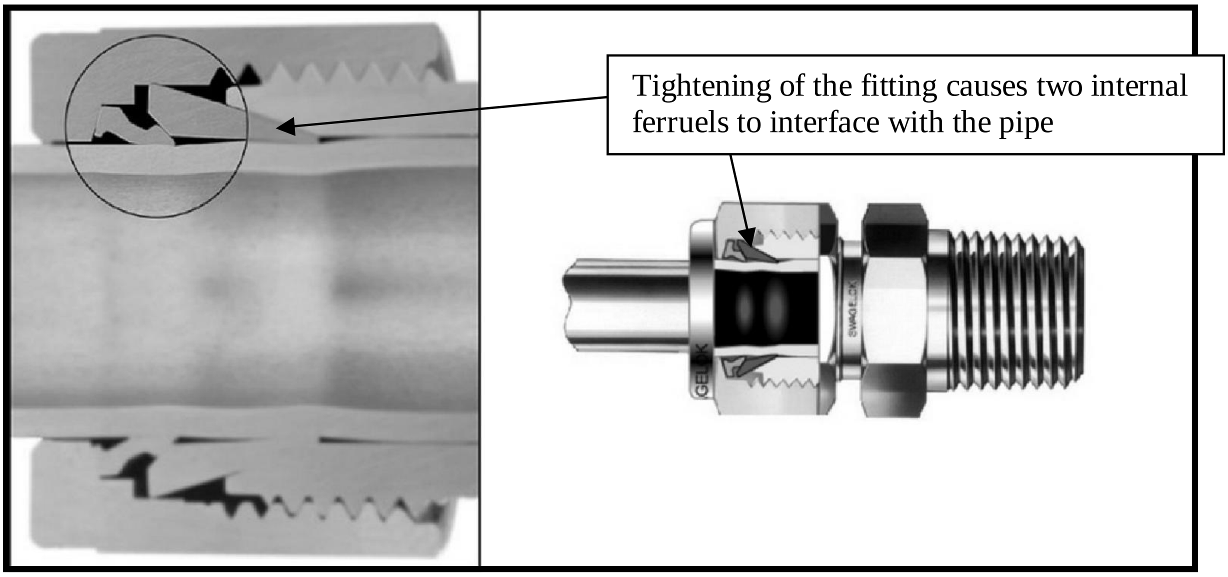


Figure 36: Swagelok® fitting

3.3 Brazing

Brazing is commonly used as a joining method on Tokamaks, specifically for joining dissimilar materials such as beam transmission windows and plasma facing components. Brazing also has a long history of being used for pipe joining and is therefore of interest to this research as a potential solution to the research objective outlined in section 1.6. Re-melting brazed joints and disassembling plant seems an obvious property of brazing. As we will see later in this work it is not quite so simple.

Brazing is defined as a method of joining that produces coalescence of parent materials by heating them in the presence of a filler metal with liquidus above 450 ˚C and below the solidus of the parent material [Kalpakjian 1995]. The key parameters for consideration when brazing are:

- Capillary attraction and wetting
- Temperature, time, rate and source of heating
- Surface preparation and atmosphere
- Joint design and clearance

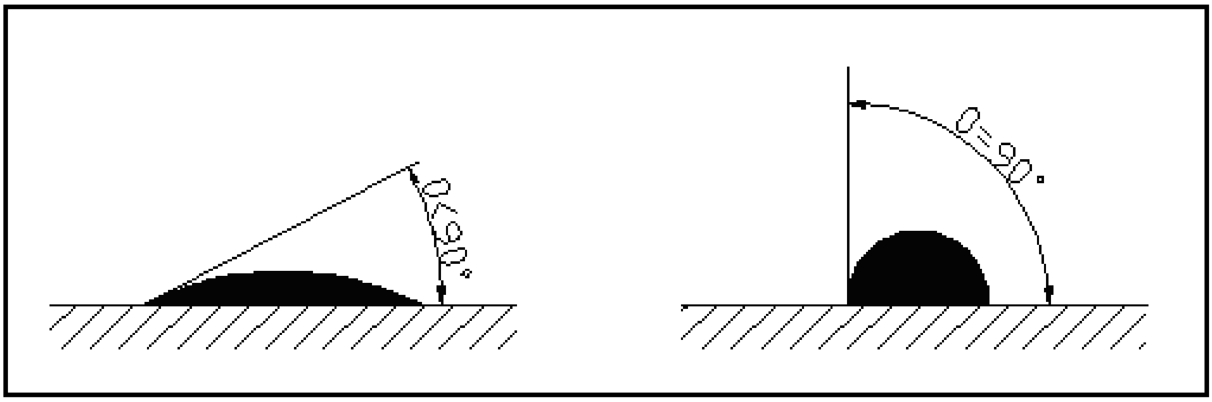


Figure 37: Contact angle as a measure of wettability – low contact angle (left) good wetting, high contact angle (right) poor wetting

Wettability can be inferred from the contact angle between the molten filler material of given mass and the parent material, see figure 37. Good wetting is characterized by a small contact angle implying the adhesive force between the liquid and the solid (+ gravity) is greater than the cohesive force of the liquid. In order to form a strong joint good wettability must be achieved.

Brazing has been used in the nuclear field where welding was not possible or difficult. Examples of this in fission can be found in fuel rod spacers and in tube to sheet joints for steam generators. In nuclear fusion brazing has been used for attaching plasma facing components and in vacuum window applications.

3.3.1 Brazing Stainless Steels

Brazed Stainless Steel joints have been used widely and as such information can be found in the literature to optimize this process. Solutions for brazing Stainless Steel s tend to be dependent on the specific Stainless Steel alloy in question. Generally speaking brazing Stainless Steel is more challenging than for carbon steels due to chromium related problems with wettability and the more arduous service requirements associated with Stainless Steel s. Wettability indexes for various grades of Stainless Steel are available, aiding the selection of filler material [Schwartz 2003].

The effects of neutron irradiation on the structural integrity of brazed AISI 316L Stainless Steel joints have been investigated. Tensile, fatigue and impact tests have been performed on both irradiated and un-irradiated specimens. Increased embrittlement was observed along with increased yield stress and Ultimate Tensile Strength (UTS) in irradiated samples [Brossa 1994].

3.3.2 Brazing in Fusion Technology

There is already a good precedent for the use of brazing in fusion technology, the following section touches on experience already gained in this area.

3.3.2.1 Joining Dissimilar Materials

Brazing has been investigated as a method of joining plasma facing armour to copper based heat sinks as part of the ITER development programme. Brazing is an attractive technology for this application as it can be used to create a joint with good thermal conductance between dissimilar materials. The plasma facing components for the ITER Divertor consist of carbon fibre reinforced carbon and tungsten tiles. Prior to 1997 high temperature brazing using a silver based braze was the preferred joining method, subsequently silver was deemed undesirable due to transmutation to cadmium under neutron irradiation [Odegard 1998]. Since then silver free braze materials have been investigated for this application, recently a copper-nickel-germanium braze with added carbon fibre filler has been shown to be effective. Subsequent investigations into the magnitude of the problem of cadmium volatilisation into plasma have found such losses to have an upper limit of 0.13% [Peacock 1996]. At present no definitive answer on the current acceptability of silver in vessel is available.

3.3.2.2 Vacuum Tolerant Brazed Joints

A range of vacuum/tritium tolerant windows are used in fusion machines. One example of this is a diamond window for an Electron Cyclotron launcher, developed in preparation for ITER. A copper coated diamond disk was successfully joined to an Inconel cuff using an Aluminium braze. The window allows efficient transmission of RF power while creating an effective vacuum and tritium barrier [Takahashi 2005]. Similarly a RF vacuum window has been developed at JET as part of and Ion Cyclotron Resonance Heating system. In this case an alumina window was joined to a titanium housing using a palladium-silver braze [Walton 1999].

3.3.3 In Place Induction Brazing

Tube-in-place induction brazing technology has been used to produce hydraulic joints in the aviation industry. Tooling consists of an atmosphere control chamber with integral inductor and clamping function. A sleeve union joint design is used with additional features for braze material location. For AISI 304L Stainless Steel hydraulic piping, an 82Au-18Ni filler metal with 950 ˚C melting point was used in an atmosphere of dry argon. Ultrasonic NDT methods have been used in conjunction with this technology.

3.4 Evaluation of Alternative Technology Options

The search for an alternative pipe jointing solution to *cutting and welding* capable of UHV applications that is also easily disassembled presents an obvious solution, *the bolted vacuum flange.* Access to key specialists during this research working in the field of Tokomaks and Remote Handling has as provided valuable *return of experience* data, not all necessarily reported in the literature. During the design and operation of JET, the use of bolted or mechanically clamped vacuum flanges for in vessel applications was prohibited. The reason for this is self-evident: should sufficient relaxation of the clamping mechanism or an off-normal load occur, the seal can potentially become disrupted causing the joint to fail. We have seen from examples in the literature that the Conflat type bolted flange has been observed to fail under repeated temperature cycling.

To take an anecdote from the JET history, during one plasma shot a particularly violent plasma disruption occurred. A disruption is what happens when the plasma is spontaneously extinguished and the electrical current stored in the plasma is discharged through the machine structure. This event is so violent that it caused the some 3500 ton tokomak to ‘jump’ from its mounting points. The event was registered by local seismologists.

These are the kind of off-normal loading conditions that can be expected in a fusion reactor. The possibility that the sealing interface can become disturbed during such an event resulting in an unacceptable leak, possibly requiring a repair makes the bolted or mechanically clamped vacuum flange an unattractive option, one that is prohibited from use on in vessel applications for both JET and ITER based on return of experience and the self-evident nature of the inherent weakness.

Having studied three candidate non-permanent/reversible pipe jointing technologies an evaluation and selection exercise was performed with respect to the design criteria outlined in the introduction. Brazing was chosen as the preferred technology primarily due to its inherent strength. Brazing produces a metallurgically bonded joint that is in principal as strong as welded joint. For both the SMA and bolted type joints sealing is affected by compression or clamping; should the compression medium be compromised or relaxed in some way the joint will fail. Comprehensive data on the performance of SMA under neutron irradiation is not available in the literature and therefore SMA represents a less attractive option. To make best use of the limited shape change offered by SMAs small assembly tolerances are required which are not appropriate for remote assembly. For the Conflat type bolted flange joint failure has been observed under repeated temperature cycling, a relatively non-violent stimulus compared with a plasma disruption. The Helicoflex seal is designed to mitigate this type of occurrence by integrating a degree of flexibility into the seal. Nonetheless it is self-evident that should sufficient relaxation of the clamping mechanism or an off-normal impact load occur, the seal can potentially become disrupted. The joining force offered by the bolts is biased along the axis if the joint to produce the sealing force and the joint is vulnerable to torsional and shear loading. The brazed joint does not suffer from these weaknesses as the metallurgical bond in principal offers strength comparable to that of a welded joint under all loading conditions.

It was necessary to perform a Trade-off Analysis to fairly compare the alternative jointing technologies. Trade-off analyses are an analytical method for comparing concepts against pre-defined design criteria [Daniels 2001].

Their use in the product development lifecycle is now commonplace following a concept generation task or similar activity.

Table 3 summarises the suitability of the jointing options discussed to RH with respect to key operational parameters.

The alternative jointing technologies were rated 1 – 10, 1 = poor and 10 = excellent against the engineering design criteria. A weighting factor was used to give the necessary priority to each design criteria. The principal requirement is for the joint is for it not to fail in an arduous environment including, temperature variation and high transient loads. Strength was therefore given the greatest priority and weighting. Similarly durability and radiation tolerance are basic requirements for joints used inside the VV.

The un-weighted results show that in accordance with our intuition, the mechanical flange joint is a clear winner. Only when the results are moderated with the necessary weightings do we see the mechanical flange type joint fall into a more realistic 3rd place due to its inherent mechanical weakness. Throughout the process SMAs hold a weak position, due principally to their reliance on compression forces to maintain sealing resulting in poor durability and strength. Their poor performance in two-way shape memory and poor radiation tolerance are also important factors.

Brazing comes out on top based on the assumption that it has comparable strength and durability to the welded joint with the huge advantage that the brazed joint can be separated simply by heating.

			Alternative jointing methods			
		Weighting	Welding	Brazing	SMA	Mechanical
Design Criteria	Reversibility	*2.0 X*	1	8	8	10
	Strength	*4.0 X*	10	10	3	3
	Durability	*4.0 X*	10	10	3	3
	Rad tolerance	*2.0 X*	10	8	3	8
	Tooling complexity	*1.0 X*	4	6	6	8
	Fit-up	*1.0 X*	2	2	2	7
	Re-usability	*2.0 X*	5	9	5	9
	Time	*1.0 X*	2	4	6	8
Score		*un-weighted*	44 *3rd*	57 *2nd*	36 *4th*	56 *1st*
		weighted	120 *2nd*	142 *1st*	70 *4th*	101 *3rd*

Quantitative rating value range 1 - 10 1 = Poor, 10 = Excellent

Table 3: Suitability of jointing options for RH

4 THEORY DEVELOPMENT OF RH REVERSIBLE BRAZE PIPE JOINT

Having selected brazing as the preferred jointing technology, the next step of the research was to develop a Remote Handling compatible joint design. This chapter covers the development of the braze formulation and the joint geometry.

4.1 Reversibility of Joint

The foremost requirement for the proposed technology is the ability to repeatedly assemble and disassemble the pipe joint. A brazed joint can in principal satisfy this requirement due to the distinct difference in melting temperature between the parent/base metal and filler metal, permitting re-melting of braze filler material without destroying the base metal parts. However, reversibility or the ability to re-melt is rarely a consideration for brazed joints, and in many cases the brazed assembly physically cannot and moreover is never intended to be re-melted and disassembled. Careful attention must be paid when formulating the brazed joint in order to achieve the reversibility property.

There are various filler metal/base metal interactions that can be detrimental to successful re-melting and separation. The most significant of these is excessive alloying which occurs at varying degrees of severity depending on the braze formulation and heating cycle. Alloying is a general term covering most aspects of base metal/filler metal interaction. All successfully brazed joints reversible or otherwise have undergone some degree of alloying, by virtue of the positive interaction or metallurgical compatibility between base and filler metals. The brazed joint starts to become difficult to re-melt when alloying occurs to the degree where the parent metal partially dissolves into the filler metal resulting in a raised liquidus temperature of the filler metal. Ultimately alloying occurs to the point where the distinction between the filler and the parent parts is lost, the joint becomes homogenous and the part becomes inseparable [Schwartz 2003].

Equally detrimental to the re-melting property is the occurrence of some diffusion bonding in the brazed joint. Diffusion bonding is a distinct material joining phenomenon in its own right, characterised by an exchange of atoms across the joint interface. Diffusion bonding occurs when two components are brought together and heated with the addition of a compressive joining force. Diffusion bonding occurs to a greater extent in brazed joints where long heating cycles are used. Once the filler metal has become fully alloyed with the parent metal, diffusion bonding starts to occur increasing the homogeneity of the joint and reducing the potential for separation.

A literature search was performed to identify examples of brazing techniques formulated specifically for the re-melting property. Very few examples were yielded as disassembly of brazed joints is rarely a consideration.

4.2 Sandia Re-braze Technique

An example of brazing being used as a functional method for joining and purposefully disassembling is presented in the following.

4.2.1 Introduction to Sandia Re-braze Technique

A braze/de-braze technique was successfully developed at Sandia National Laboratories as a method of attaching/sealing and reopening a recyclable radioactive material transport container [Walker 1995]. The container consists of a cylindrical body and screw thread lid, when closed a filler alloy perform is trapped between sealing lands prior to heating, see figure 38.

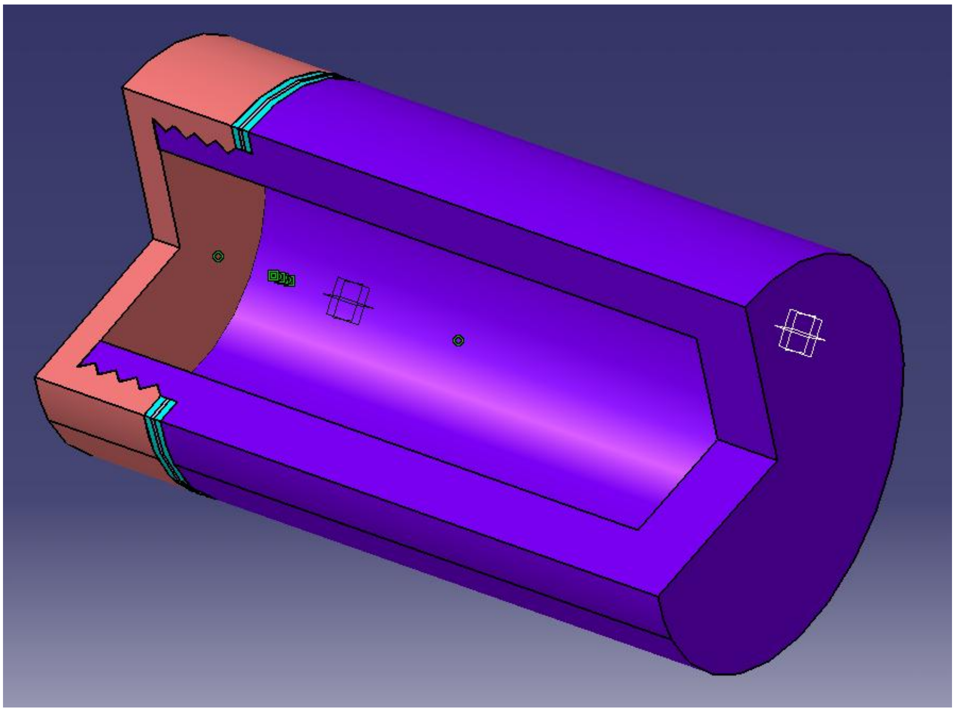


Figure 38: Re-braze-able Sandia recyclable radioactive materials container

A brazed type seal was selected due to its integrity at high temperatures and its mechanical strength - a properly designed brazed joint has the same strength as the base material. Electromagnetic induction heating was used allowing the braze to be performed in-situ, a key requirement for the system. Brazing was performed in an inert gas atmosphere of helium. The process was performed up to 20 times without the need for special refurbishment of the joint interfaces.

4.2.2 Development of Re-braze Technique

The principal challenge encountered during the development of the project was the issue of reversibility. A range of braze alloys and inert gas arrangements were studied. During initial trials AISI 304 Stainless Steel samples were repeatedly brazed together which under metallographic analysis exhibited base metal dissolution and grain growth, both detrimental to the structural properties of the AISI 304 Stainless Steel base metal. A stable interface material to create a boundary between the re-braze join and the Stainless Steel , preventing dissolution between the two was sought, Nickel-

200 was found to perform this task effectively. Initially the interface was made using a braze deposited layer, resulting in improved preservation of the base parts however following further analysis a thicker layer of Nickel was required.

The 82Au-18Ni alloy was found to produce the best re-braze results when used with the Nickel interface layer, see figure 39.

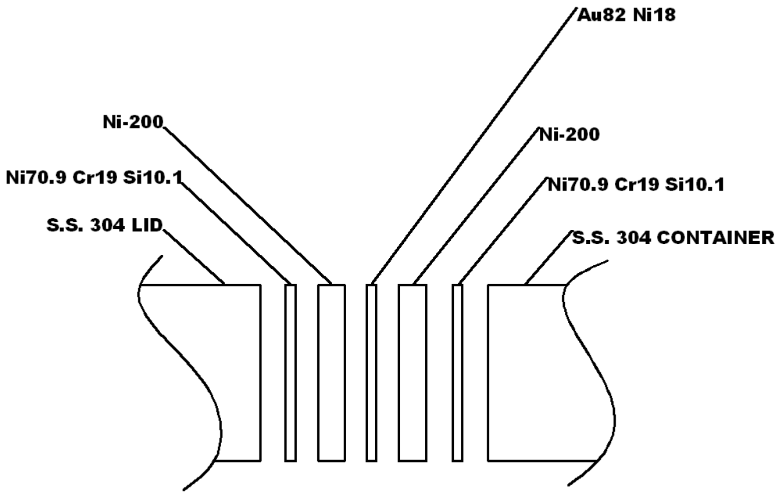


Figure 39: Braze formulation

Multiple samples were brazed and de-brazed 20 times, with a helium leak test each time the parts were joined. Additional braze alloy performs were added for each join cycle, no base metal surface preparation was required between each braze cycle.

The basic joint design reported by Sandia is not suitable for the type of pipe joint sought here. Furthermore, no data concerning the structural quality of the brazed joint was given. Both of these issues are addressed in this research.

4.3 Joint Design

Having identified a potentially suitable braze formulation the next step of the development process was to design a joint capable of exploiting it. This section presents the development of the joint geometry.

4.3.1 Sleeved Joint

The conventional brazed joint design for a pipe or tube is the sleeved joint. A concentric cylindrical union fitting/sleeve is positioned over the pipe joint, lending good structural support under bending and shear conditions. Torsional and axial stresses are borne by the braze alloy. Comprehensive published data for brazed joint failure stress for specific base/filler formulations is unobtainable due to the various parameters involved in the brazing process and the difficulty in precisely controlling aspects such as joint gap and surface finish for example. For safety critical brazed systems practical bench trials and destructive testing are necessary to determine the true mechanical characteristics of the brazed joint in question. For sleeved joints a general rule is applied to achieve good joint strength: the overlap of the sleeve on the base metal pipe/tube is equal to 3 times the thickness of the tube/pipe wall thickness. Once the assembled joint is at brazing temperature filler metal is applied at the edge of the joint and drawn in via capillary action. Alternatively filler metal is pre-placed in a machined feature on the inner face of the joint sleeve. As the joint is heated the filler metal melts and is distributed throughout the joint via capillary action.

From the perspective of RH the sleeved joint has a number of drawbacks. Joint clearance must be precisely controlled in order to optimise the capillary force responsible for filler metal distribution; generally clearance should be 0.05 – 0.13 mm.

For RH pipe jointing applications accurate alignment poses a particular problem; the lack of human intervention limits confirmation of successful alignment and as discussed thick-walled pipes have low compliance and are intolerant of the strain required for alignment. Assuming axial and coaxial misalignment of 0.5 mm as stated for the Divertor pipe maintenance scenario [ANSALDO 2004] with a further 0.1° angular misalignment, achieving the uniform clearance required for capillary action to take place in the sleeved joint becomes impractical.

Furthermore sliding the sleeve into position prior to brazing may be prevented by poor alignment. Similarly, if some distortion in the pipes or related components has occurred during service resulting in accumulation of stress across the brazed joint, the sleeved component may become jammed during de-brazing complicating removal.

In addition refurbishment of the cylindrical external surface of the braze interface on the pipe presents a more challenging task than say a flat end face. There is also the difficulty of cleanly removing the sleeved component during de-brazing without encountering some degree of re-solidification mid-process; continued heating would be required during removal.

4.3.2 Butt Joint

The butt joint is one of the simplest brazed joint designs, in the context of pipe/tube joining the braze surface area is increased with the addition of a flange feature thereby increasing joint strength see figure 40.

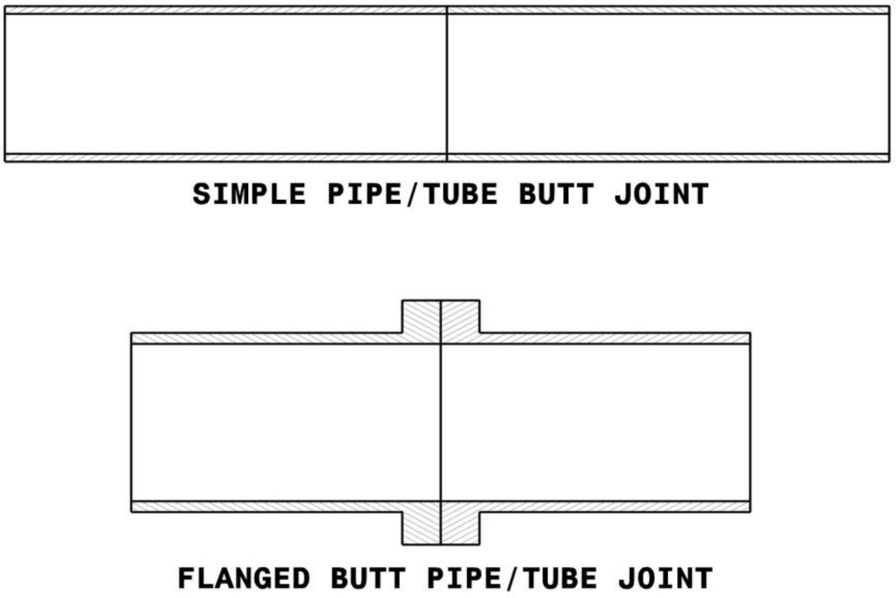


Figure 40: Simple butt joint and flanged butt joint

4.3.3 Braze Filler Preforms

The principal attraction to using a butt joint design over the sleeved type is the capability to use braze alloy performs. Braze pre-forms are available as stamped shapes which are built in as part of the assembly and then heated to complete the brazed joint. The advantage of using preforms is that the thickness and distribution of the filler metal can be predetermined, without having to rely on capillary action to distribute the filler metal throughout the joint. For a flanged pipe joint design, a washer perform can be sandwiched between the two flange halves prior to heating, see figure 41.

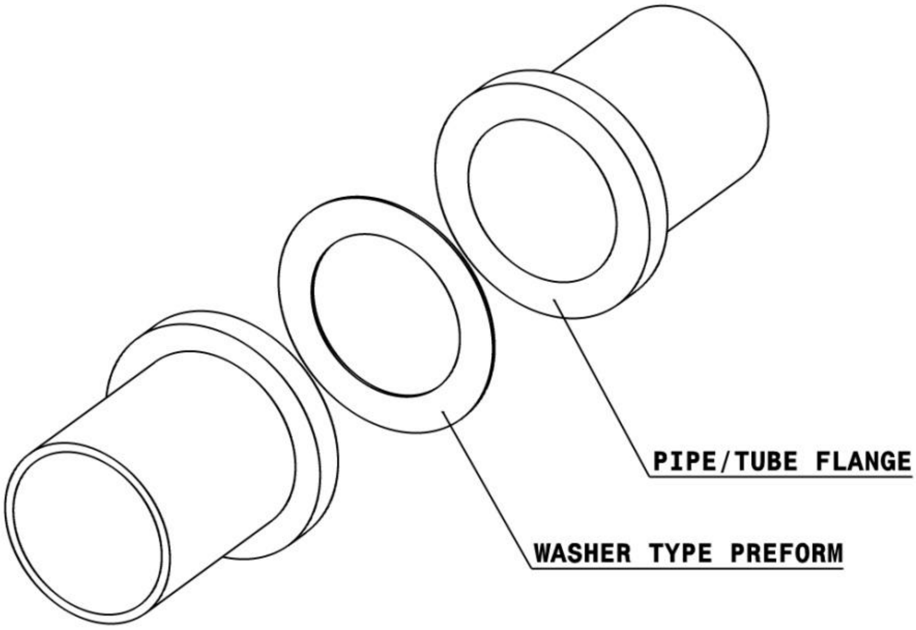


Figure 41: Flanged joint with washer type preform

To achieve the same degree of filler metal thickness and distribution with a sleeved joint a cylindrically shaped perform is required. The preform would be assembled into the sleeve prior to installation at the joint. Given the potential for misalignment of pipe stubs and the tight tolerances necessary for brazing, some damage to the braze preform could be expected during installation at the joint, thus further limiting the practicality of the sleeved joint design.

4.3.4 Reinforced Butt Joint

The basic structural requirement for both the pipe and pipe joint is to tolerate the pressure differential between the medium inside the pipe and the external environment. In the context of ITER in applications such as the Divertor, off-normal loading conditions such as plasma disruptions, thermal distortions and alignment errors will demand higher structural integrity of the joint.

For the unsupported butt joint, bending, shear, axial and torsional stresses are all borne by the brazed interface unlike the sleeved joint where mechanical reinforcement is provided by the structure of the sleeve element. One particular concern for the butt type pipe/tube joint is its susceptibility to ‘peel’ under bending conditions. Under bend type loading stress accumulates at the outer extremity of the butt join, irregularities in the braze fillet at the joint edge have the potential to form small cracks under this type of loading which could propagate along the braze interface resulting joint failure.

Mechanical reinforcement such as bolting can be used to carry some of the load thereby reducing the stress experienced at the braze interface, see figure 33.

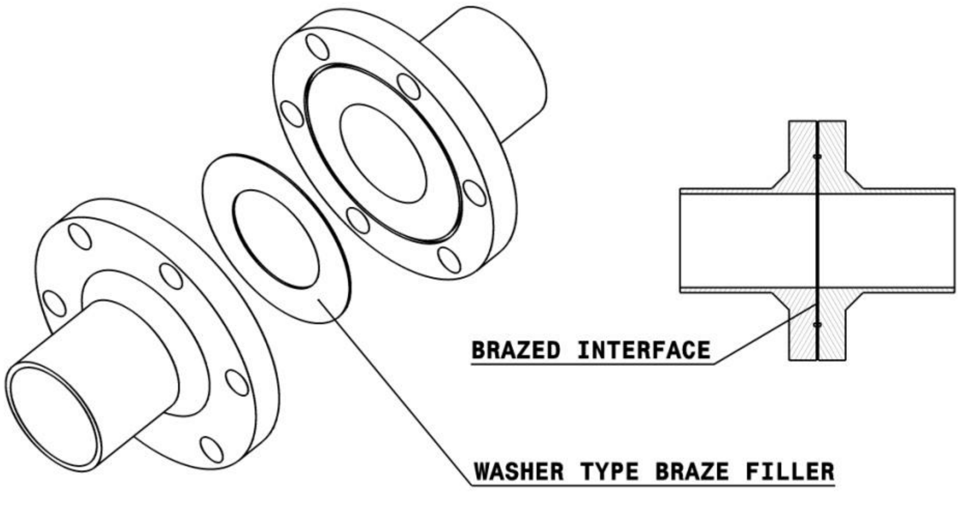


Figure 42: Simple butt braze with bolted reinforcement

4.3.5 Regulating Stress in the Brazed Joint

In the simple reinforced, flanged butt joint shown in figure 42 the brazed interface still makes up a major part of the load path in parallel with the bolted reinforcement. Regardless of the structure of the flanged reinforcement the brazed joint cannot be completely shielded from the load path.

By introducing a flexible element to the structure supporting the brazed joint and maintaining relatively high stiffness in the reinforcing flange the brazed joint becomes segregated from the load path, see figure 43.

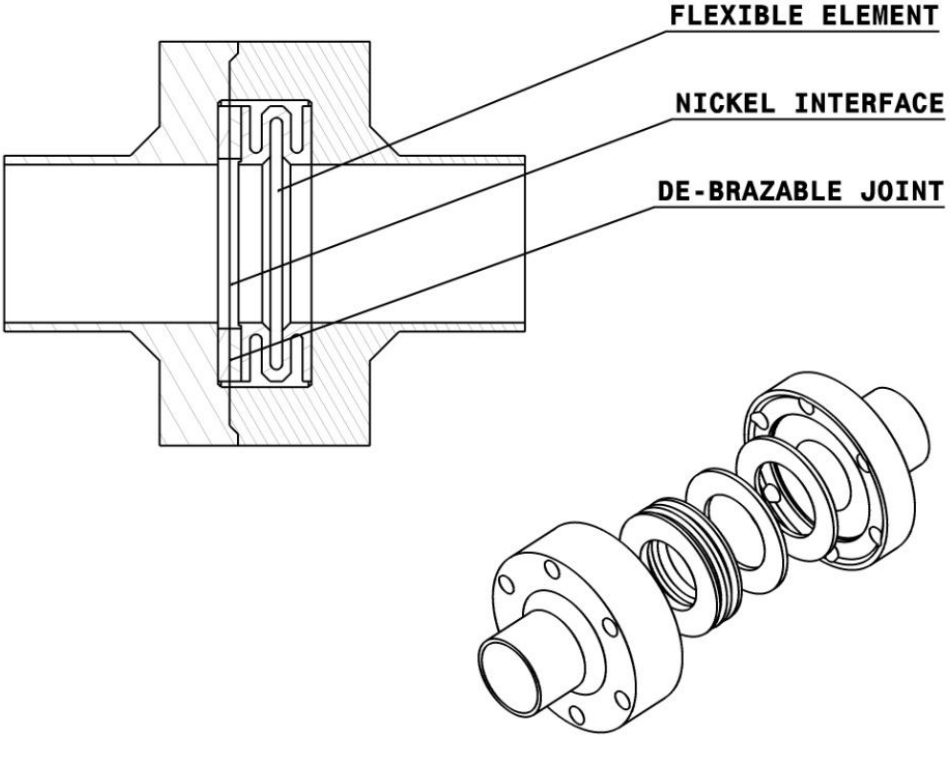


Figure 43: Reinforcing flange with low stiffness element

This principal can be appreciated in the simplified model, created using the finite element method, see figure 43. As the load is applied the combined structure is inclined to deform along its length. The rigid outer structure resists deformation while the flexible convoluted design of the inner element has a much greater capacity to deform. Consequently the outer structure becomes stressed to a higher degree than the inner section and the central box section is shielded from the load. The higher stress is illustrated in figure 43 by the brighter colouring. The stress separation property was shown to be constant over various load cases, assuming a constant material across the component.

The purpose of the simulation, figure 43, is to show the relative difference in stress in the rigid and flexible elements.

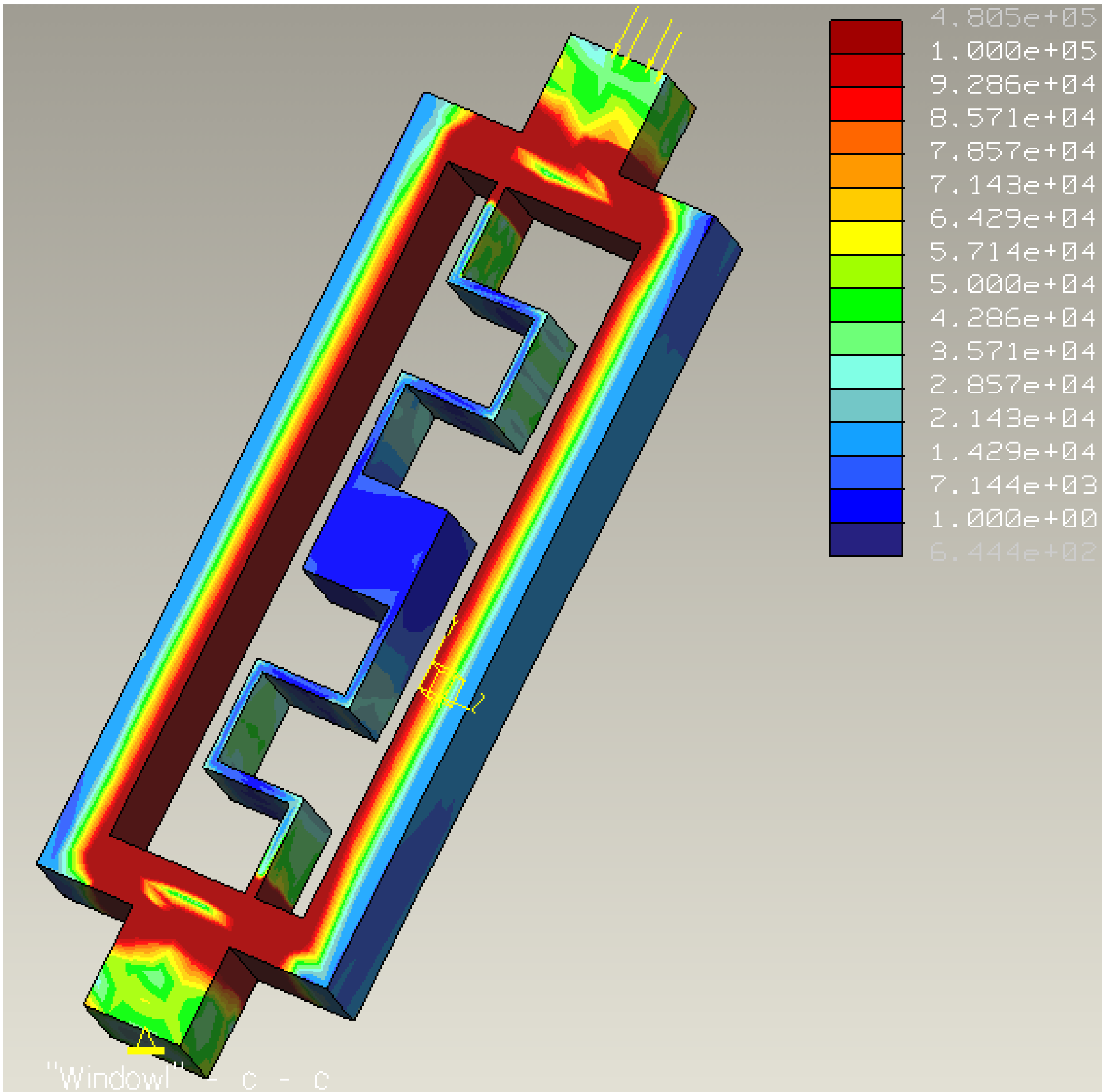


Figure 44: Finite Element Model of load segregation by introducing a stiffness offset

In order to optimise the shielding effect the maximum distinction between the high stiffness of the reinforcing flange and the low stiffness of the flexible element must be achieved. Minimising the stiffness of the flexible element is limited by the requirement to tolerate the pressure of the medium in the pipes.

The process of defining the relative stiffness of the reinforcing flange and the flexible element therefore begins by addressing the structure of the flexible element with respect to pressure requirement. The resultant stiffness of the flexible element is then calculated and a target stiffness value for the reinforcing flange can be set.

4.3.6 Defining the Structure of the Flexible Element

The two dominant parameters limiting the lower stiffness value for the flexible element are the wall thickness and length of the convolutions. Of principal concern is the wall thickness which must be sufficient to tolerate the pressure of the fluid inside the joint.

Defining the appropriate wall thickness begins by identifying the most probable failure mode for the element. Three potential failure points A, B and C are considered, see figure 45. Failure mode B represents a failure along the axis of the element at the outer bend in the convolution. Failure mode B represents a failure along the axis of the element at the inner bend in the convolution. Failure mode A represents a failure in the direction perpendicular to the axis of the element.

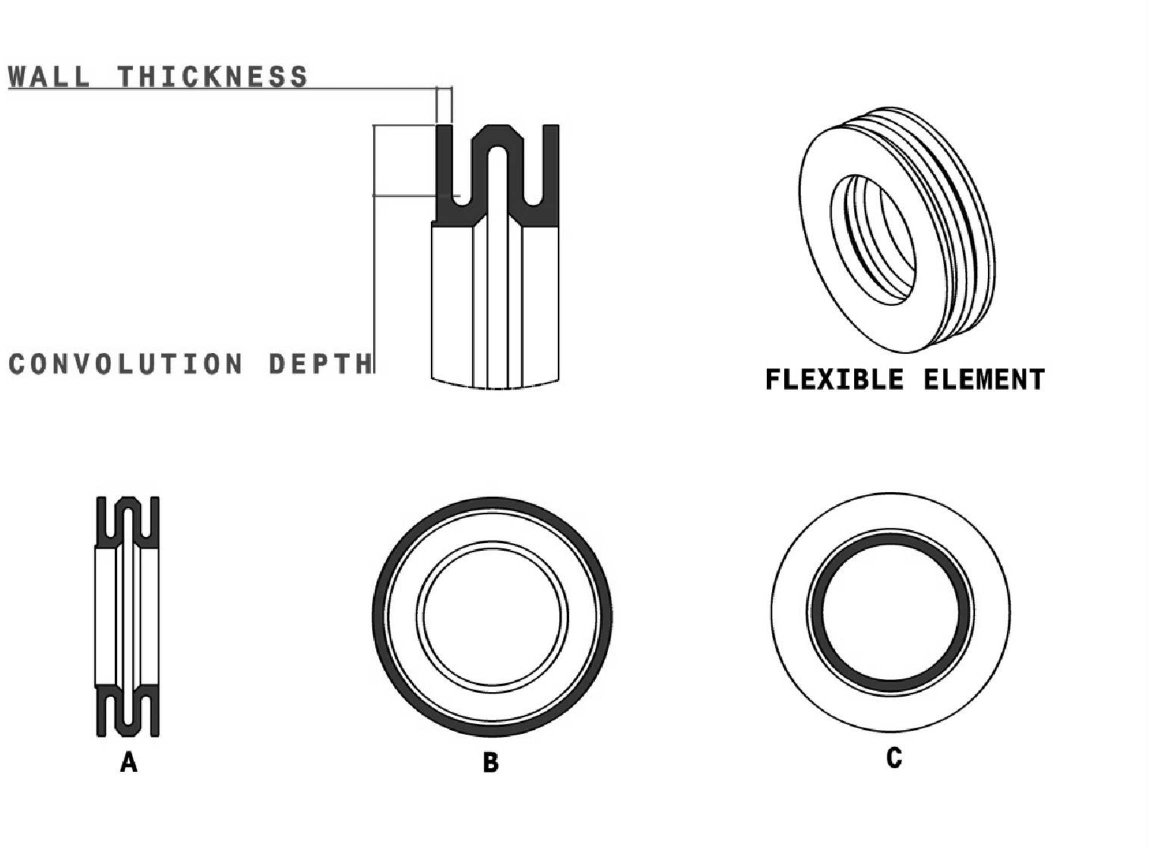


Figure 45: Failure modes considered for the flexible element

Failure mode B has the lowest cross sectional area compared to the area over which the pressure of the fluid can be exerted compared to A and C, and therefore is the weak-point of the component. The wall thickness must be sufficient to resist the force exerted by the fluid acting over the area at failure mode B.

The total force exerted by the fluid acting over this area is calculated, given the Ultimate Tensile Strength (UTS) of the flexible element material the minimum necessary cross sectional area can be defined.

As the depth of the convolutions of the flexible element increase, so does the area over which the pressure of the fluid acts on failure point B. The wall thickness must therefore be reassessed if the convolution length is adjusted.

4.3.7 Calculating Stiffness in the Flange and Flexible Element

The relative stiffness of the reinforcing flange and the flexible element can be determined using the Finite Element Analysis method (FEA), alternatively standard formulae are available for a limited variety of geometries. The flexible element can be compared to a corrugated tube, for which the following equation is given to calculate deflection,

Equation 3: Displacement of a convoluted element

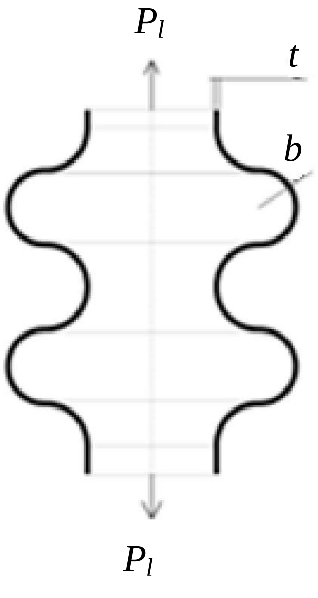


Figure 46: Illustration for equation 3

Where the applied load is $\boldsymbol{P_l}$, ***b*** is the radius of the corrugation/convolution, ***n*** is the number of corrugations, ***E*** is the Young’s Modulus of the material, ***v*** is Poisson’s ratio and ***t*** is the wall thickness of the element [Young 1989].

Calculations for stiffness using FEA versus equation 4 were found to be in good agreement. No standard formula representing a reasonable approximation of the reinforcing flange could be sourced.

A full joint was modelled based on a Schedule 40 pipe, flange Ø OD 70 mm, flexible element wall thickness 0.75 mm. When the assembled the joint was analysed for stress using the FEA method, the flange was exposed to 35 times that of the flexible element when using two flexible elements each with two convolutions, see figure 46.

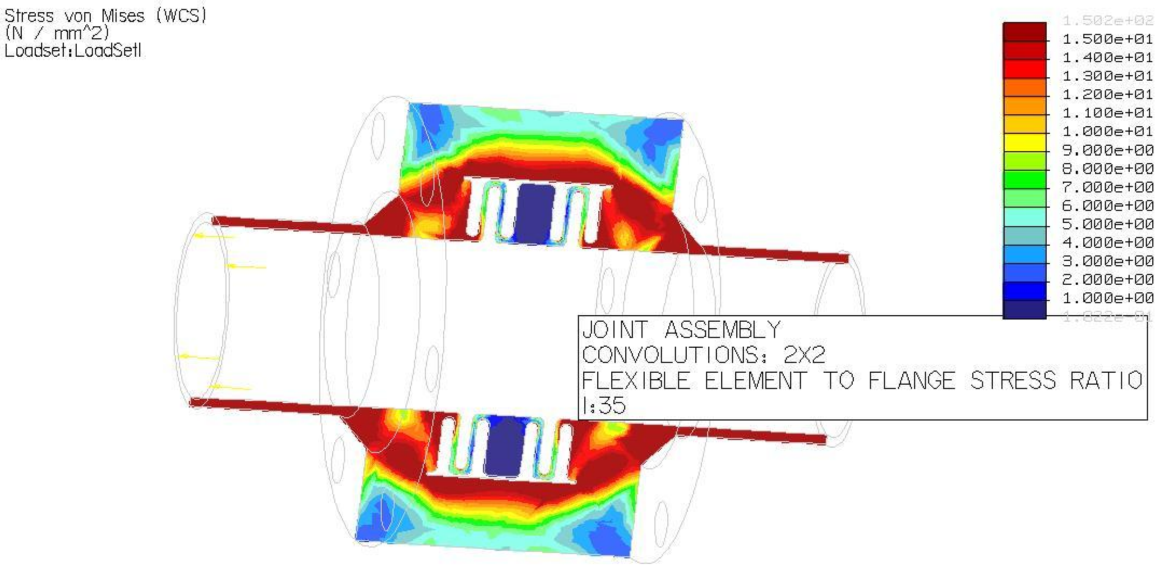


Figure 47: Joint analysed for stress with double convolution

For a joint assembly using two flexible elements each with only one convolution roughly half the relative exposure to stress was observed see figure 47.

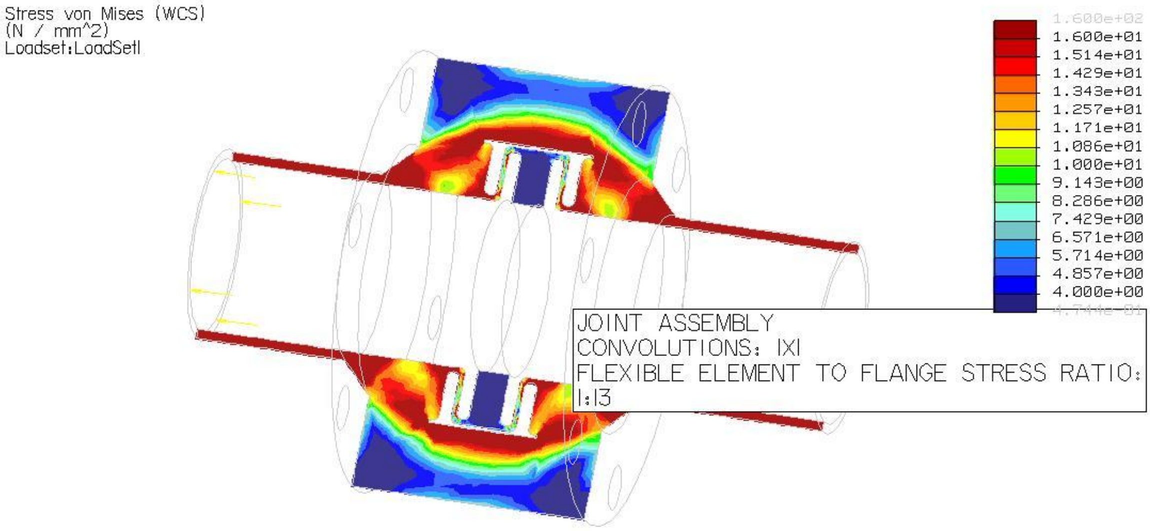


Figure 48: Joint analysed for stress with single convolution

The FEA simulations performed to create figures 46 and 47 assumed AISI 316L Stainless Steel throughout the geometry. Load cases in the region approaching tensile failure at the 2 mm wall pipe section either side of the flange geometry were used.

Multiple simulations with varying loads and geometries were made. The results showed as expected that the separation of stress between the relatively stiff flange and the flexible element was relatively constant irrespective of the load. Indicating that given a constant material the geometry of the joint is dominant in creating the stress segregation property.

4.3.8 Accommodation of Misalignment

An additional advantage of the flexible element is the ability to tolerate a small degree of angular axial misalignment. As the joint is clamped and pulled together it can deform to accommodate misalignment. Using the finite element model for the geometry discussed in figure 48, a nominal pulling force of 635 N was required to effect a displacement of 1.0 mm.

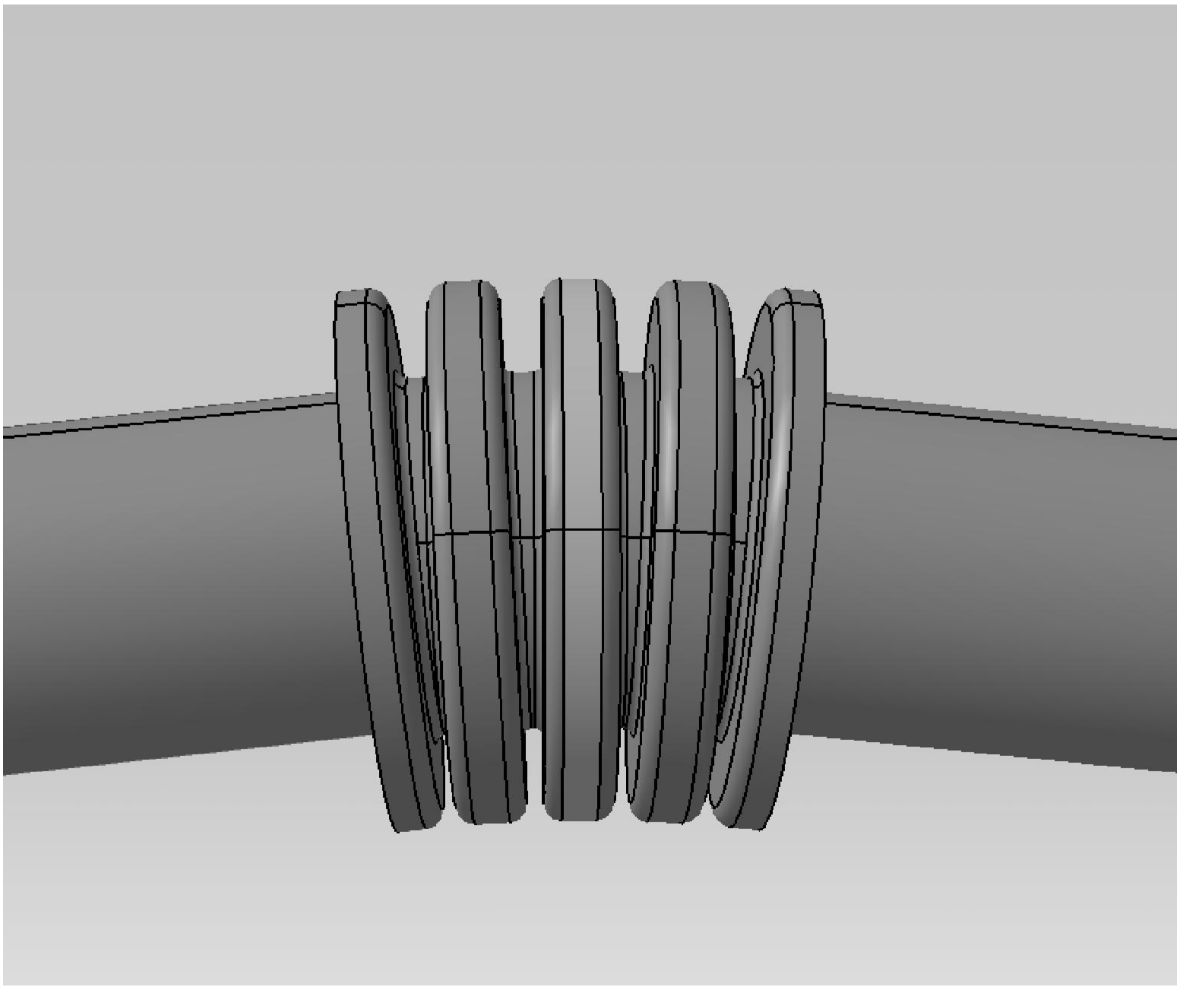


Figure 49: Angular axial misalignment

Simple co-axial misalignment can be more easily accommodated given an oversized cross-sectional area of the flanged interface on the butt joint.

4.4 Heating Method and Inert Atmosphere

Many heating methods are available for brazing such as simple flame torch, furnace, electrical resistance and microwave. Torch brazing is versatile but requires flux to prevent oxidisation during heating, leaving a corrosive residue on the joint that requires careful cleaning. Depending on the type of flux used residues can contain Chloride and Fluoride compounds that in the context of RH for fusion represent a contamination risk to plasma, moreover design guidelines for ITER state that brazing must either by conducted in vacuum or inert atmosphere [ITER 2001]. Induction heating has the advantage of portability compared to microwave for example, power generators can be stationed away from the work area with heating coils operating via umbilical tens of metres long. Localised inert atmosphere chambers can be used on continuous pipe runs in a clam shell configuration as described in section 4.3.3. Precise control of temperature can be achieved with the use of thermocouples or non-contact pyrometer sensors. Rapid heating can also be achieved, reducing the potential for diffusion bonding that can lead to a homogenous irreversible joint, generally a result of heating over a long time-period. Another advantage of induction heating is that highly localised heating can be achieved, entire heating of the part is not necessary as in furnace brazing.

Induction heating works by supplying high-frequency alternating currents to the work coil, creating a magnetic field which in turn generates eddy currents in the work piece causing ohmic heating. Water cooling is used to negate the heating effects in the metallic work coil. The induction generator is sized by taking into account the mass of the work piece, the base material of the part to be heated and its ability to absorb power:

$$P_a = \frac{W \cdot T \cdot C}{0.95t}$$

Equation 4: Calculating the induction heater power rating

Where P_a is the absorbed power in kilowatts, W is the mass of the material, T is temperature, C is the specific heat capacity of the material and t is the time required for heating. The proximity of the work coil to the work piece is critical; 0.95 is a constant used to approximate these losses.

Little data is available on the radiation tolerance of induction heating equipment. However the power generator can be situated away from the work area and connected to the work-head and coil via umbilical. The work-head consists of copper bus-bars and copper/ceramic capacitors. Polymeric insulators are used on connecting cabling. The work-head and coil therefore present good potential for radiation-hardness.

5 COMPARISON OF WELDING AND BRAZING FROM AN RH OPERATIONS PERSPECTIVE

Having developed a design for a reversible pipe joint based on brazing, the next stage of the research was to examine whether the brazed approach offers any potential practical advantages over the current state of the art. In this chapter weld/cut and braze pipe maintenance strategies are considered in terms of their overall operational burden from an RH perspective. A concept for a pipe maintenance operations strategy based on brazing is presented and contrasted against the State of the art for ITER Divertor pipe maintenance: *Cooperative Maintenance Scheme for ITER Divertor cooling pipes.* Parameters such as, total number of tasks sequence steps, total tool inventory and tooling complexity are compared. A short review of the task analysis and planning methodology used at JET was made, this exercise helped to form the basic criteria used for the comparison.

5.1 Short Review of Task Analysis Methodologies Used at JET

Over the course of 15 years of operations carried out on the JET machine by the RH department a formal methodology for planning RH tasks has evolved. This process begins with a proposal for a new assembly or maintenance task by one of the JET machine/component designers such as the installation of new plasma facing tiles or pipe maintenance procedures for example. Once an RH installation or maintenance concept has been agreed by tokomak designers and RH engineers, the process of RH task analysis and planning can begin. Figure 49 shows the principal elements of the process task, an introduction to the concepts involved in the process follows.

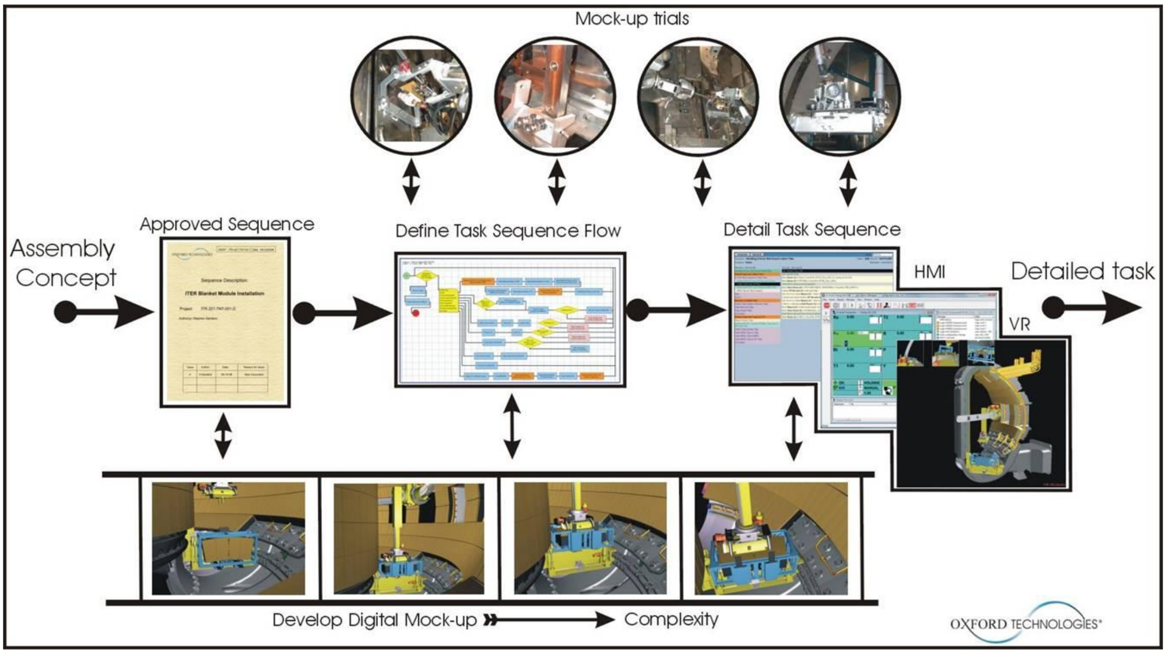


Figure 50: Holistic view of RH task planning process

5.1.1 Sequence Description Document

The first stage of the process is the creation of a Sequence Description Document. This document gathers together and categorises all the known relevant information about the task and sets out the plan for its execution. The document is organised into the following sections:

Sequence description: An overall description of the task, followed by a list of all the significant steps required to complete the task including the known relevant details for each step.

Flow control: Where multiple parts and fixture positions are a requirement of the task, a numbering system is used to identify those positions and parts.

Start and End Condition: Describes the required/resultant status of the work area prior to and after task completion with relation to preceding/subsequent tasks, covering physical locations of components, tools and movers/manipulators.

Component Specification: Provides information about components involved in the task, specifically the interfaces necessary to perform the task, including images and engineering drawings.

Equipment Specification: States the RH movers/manipulators required for the task with additional commentary on configuration.

Tooling Specification: States additional tooling to support manipulators, bolting tools, clamping tools for example.

Available Teach and Repeat files: Notes pre-existing software files, used to drive the manipulators/movers that may be of use for the task in question.

VR Model Specification: Lists the necessary VR models to simulate the task, including the task environment and colour conventions for example.

Mock-up Requirements: Details any practical bench trials necessary to qualify the task prior to final execution.

Reference Drawings and Documentation: Lists all other pre-existing relevant documentation.

5.1.2 Task Sequence Flow Chart

The task sequence flow chart describes the execution of the task step by step and is used as a guide by the RH operators carrying out the task. The flow chart is created in the Structured Query Language (SQL) database environment using simple ‘IF THEN’ logic allowing for potential uncertainties in the execution of the task thereby providing alternative courses of action or recovery from failure strategies should the primary path for the task not be possible.

5.1.3 Detailed Task Sequence

As each stage of the flow chart is created, a corresponding chronological list of necessary actions is automatically generated in the SQL environment called the Detailed Task Sequence. This is the end-product of the task planning exercise and is the focus for the operator while the task is being carried out. Each action on the list has a check-box that is marked upon its completion during the execution of the task, the time and identity of the operator is then automatically logged.

5.1.4 Mock-Ups and VR

Where appropriate physical mock-ups are made for the purpose of proving that difficult aspects of the task can be achieved and to practice procedures prior to in VV operations. Virtual Reality (VR) is used in a similar way; tasks can be performed in the virtual environment to check for potential problems such as collisions or a lack of manipulator reach for example. VR can be used to generate trajectory data for RH equipment that is then used during operations.

5.2 Method for Comparison of Braze and Weld/Cut Approaches

For the purposes of an operational comparison both the brazing and cut/weld strategies are be presented in terms of an overall ***Sequence Description***. Each strategy is then analysed with respect to the following parameters:

- ***Number of process elements***: the number of significant steps required to complete the task
- ***Total tool inventory***: the number of tools required to perform the task
- ***Tooling complexity***: rated in terms of the number of components, number moving parts, necessary scheduled maintenance.
- ***Criticality of placement***: the level of dexterity required for tool placement and

- ***Tooling maintenance***: the burden of maintenance for a particular tool

5.3 General Sequence Description for Divertor Pipe Maintenance

This section describes the Divertor Cassette replacement operation as a whole, before going into pipe maintenance more specifically in later sections.

The ITER Divertor assembly consists of 54 cassettes located in the bottom of the vacuum vessel (VV). Each cassette is mounted in the VV on inner and outer toroidal rails and connected to feed and return water cooling pipes. The cassettes need to be periodically removed from the VV for refurbishment of Plasma Facing Components (PFCs). This operation involves RH cutting and re-welding of the water cooling pipes.

Coolant feed and return pipes are routed radially through 9 Divertor level ports and through smaller special purpose vessel penetrations. Of the 9 Divertor level ports 3 are used to transport the cassettes to and from the VV. For cassettes immediately in front of the ports and those adjacent to it a dedicated RH mover/manipulator device called the Cassette Multifunctional Mover (CMM), see figure 50 is used to separate/join coolant pipe connections operating from the port duct and to transport the cassette to/from the VV [Salminen 2011]. During removal of the Divertor, once the cooling pipes have been cut, the CMM then lifts the cassette from its position and transports it out of the VV. Similarly during Divertor installation, the CMM transports the cassette into the VV, installs it at the correct location and then re-welds the cooling pipes.

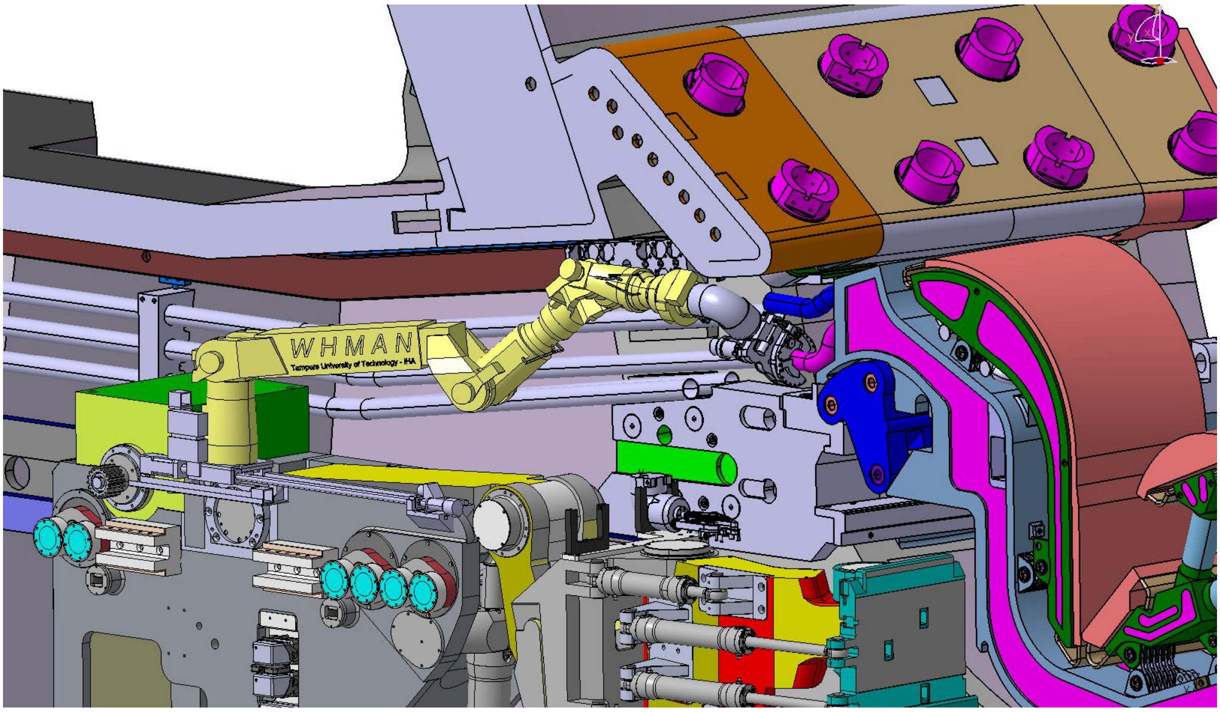


Figure 51: CMM performing pipe maintenance operations

A second RH mover/manipulator device called the Cassette Toroidal Mover (CTM) capable of operating inside the VV is used to service the remainder of the Divertor Cassettes, see figure 51. Unlike the CMM, the CTM is capable of translating around the circular path of the VV, accessing the remainder of the Divertor Cassettes, see also figure 9. Coolant pipe cutting/welding operations are performed from the CTM, see figure 50. Once the cooling pipes have been cut, the CTM then transports the Divertor Cassette to the appropriate RH Divertor level port, where the CMM then takes over, removing the Divertor from the VV and back out along the port duct. Similarly during installation, the CMM transports the cassette along the port duct, through the RH Divertor level port and into the VV, at which point the CTM picks up the cassette and transports it along the circular path of the bottom of the VV to the appropriate location. Welding of the Divertor Cassette cooling pipes is then performed using orbital weld tools deployed by the CTM mounted servo-manipulator.

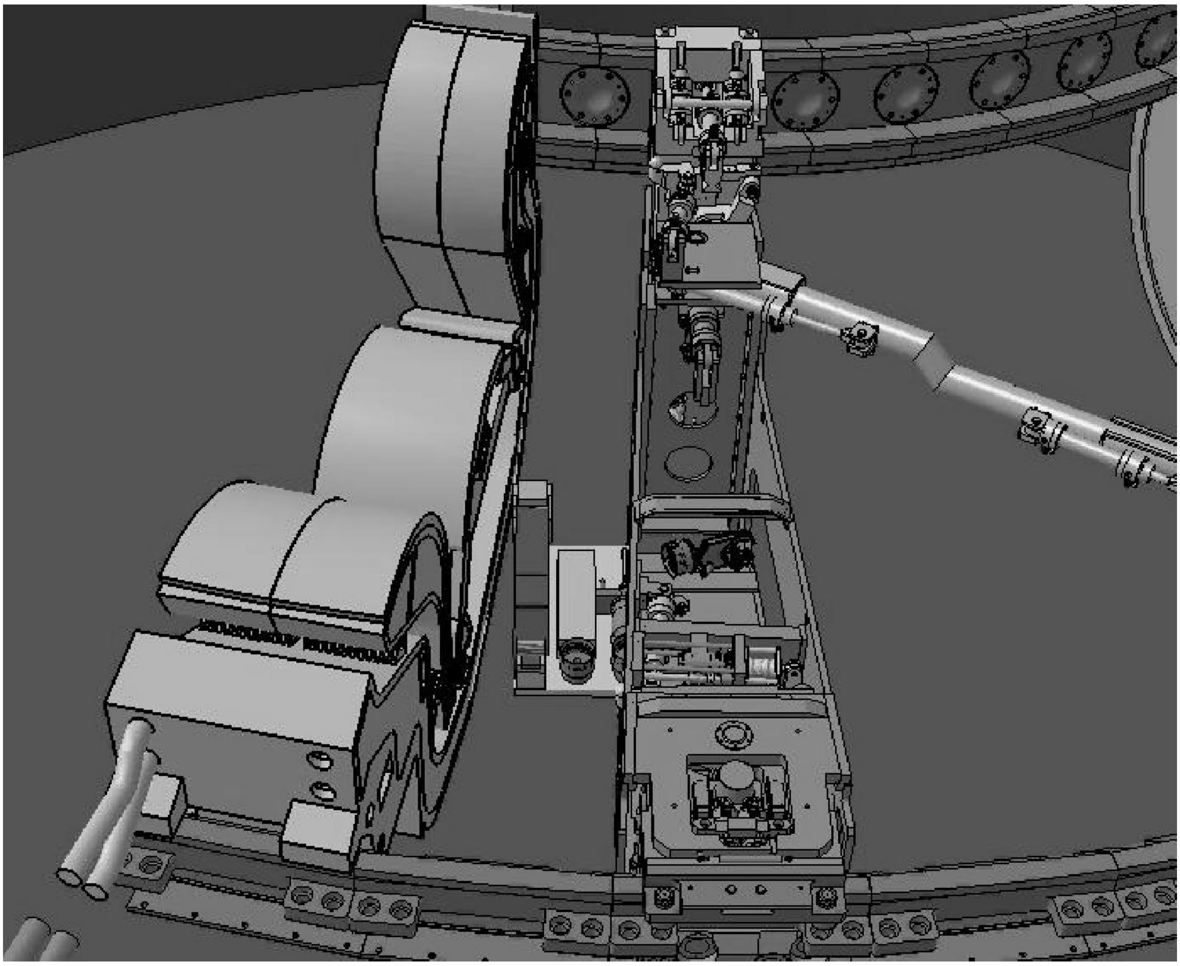


Figure 52: Illustration of CTM working on cassette inside the VV

From the port duct the CMM and cassette are loaded into a transfer cask for transportation to the Hot Cell. Once inside the Hot Cell feed and return cooling pipes between the PFCs and the cassette body are cut using a Bore Tool System (BTS) system.

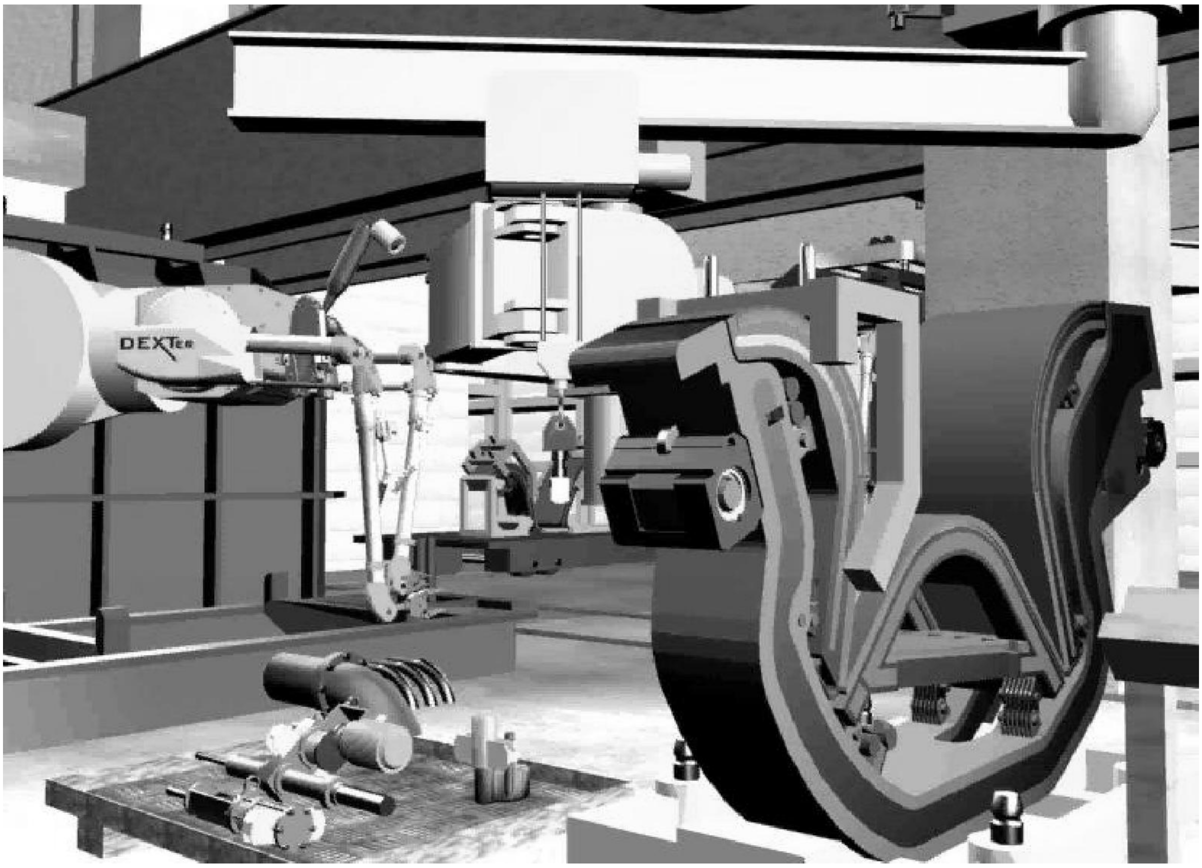


Figure 53: Illustration of Divertor Cassette disassembly in Hot Cell

Replacement PFCs are mounted, attachment fixtures added and PFC/cassette body cooling pipes are joined using a BTS welding tool. The re-assembled cassette is then transferred to a test vacuum chamber to leak test the newly welded joints on the cassette cooling pipes. Passed cassettes can then be returned to the VV in reverse order of the process described. See figure 52 for Divertor maintenance in Hot Cell.

5.4 Brazing Pipe Maintenance Operations Task Description

This section details the concept design for ITER pipe maintenance tooling based on the reversible braze technique. Concept designs for tools, giving indicative dimensions are presented. The function of the tooling and how it is deployed is explained in the context of an operations sequence, a step by step procedure for RH brazed pipe joint maintenance.

5.4.1 Sequence Description

The replacement procedure starts by positioning the BTS see figure 53 and applying a securing force, this ensures that any residual stresses in the pipe work incurred during service can be relaxed in a controlled way during joint separation.

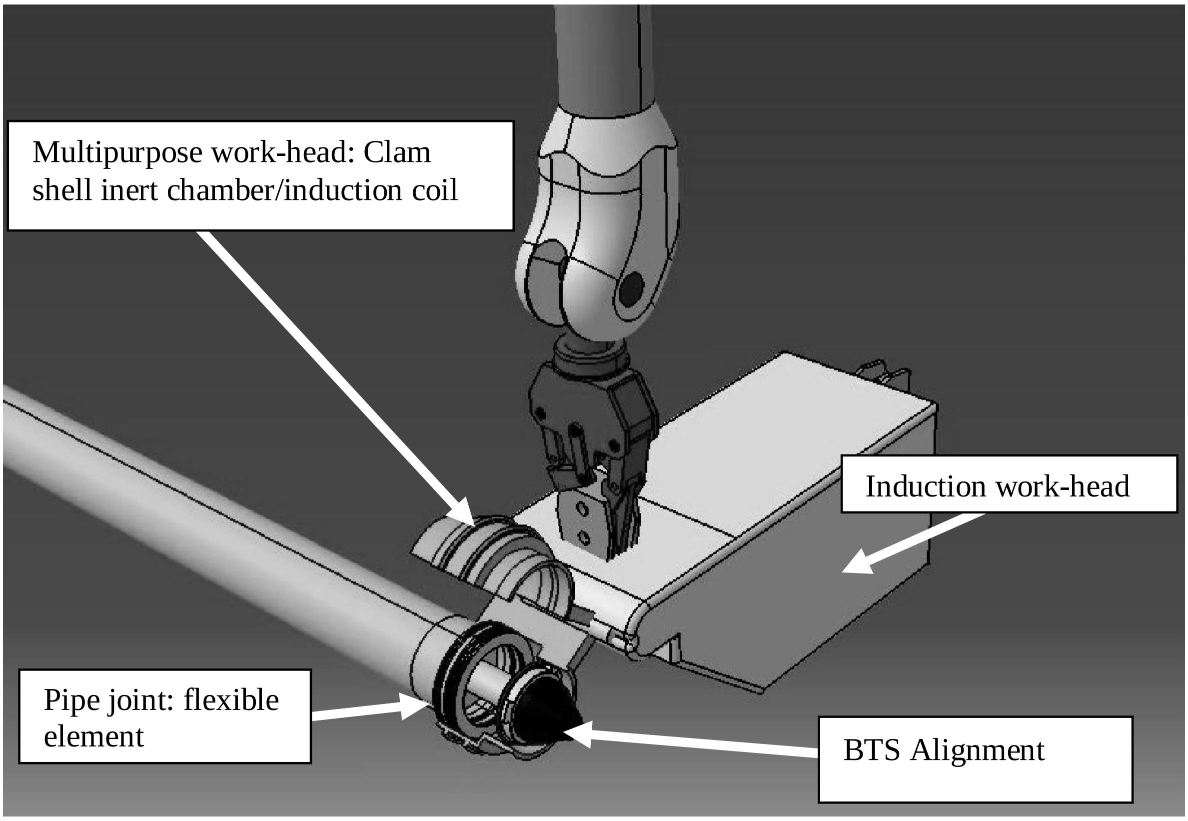


Figure 54: Multifunctional work-head positioned by manipulator

A small preload is also exerted on the joint by the BTS to assist separation of the joint during heating. The clamping mechanism (bolting/V-band flange) on the reinforcing flange is then removed using simple tools deployed using a manipulator. The loose reinforcement flange halves can then be positioned and secured away from the joint. A multipurpose work-head see figure 53 is then positioned over the joint using a manipulator. The scheme shown for the multipurpose work-head is based on similar in- place pipe induction brazing equipment used in the aviation industry [Schwartz 2003]. The multipurpose work-head shown above was not developed beyond the conceptual phase.

The clamshell type induction coil/inert chamber is then clamped shut. Once inert gas purging (used to eliminate an oxidising atmosphere that can prohibit good wetting) has been initiated in both the BTS and the multipurpose work-head, the induction coils can be energised and the heating cycle can begin. The separated joint is then allowed to cool in the inert atmosphere to prevent oxidisation. The multipurpose work-head and BTS are then removed from the work area and the machine component is ready to be removed.

Prior to positioning on the machine the replacement component is loaded with a braze foil pre-form ‘tack brazed’ into place at the joint interface. Once the component is in position the alignment BTS is deployed, a dedicated tactile metrology tool is used to assess joint fit-up. The multipurpose work-head is then re-positioned and brazing can begin. Prior to replacing the reinforcing flange an ultrasonic or He leak test inspection procedure is made to assess joint integrity. Figure 54 shows progressive stages of the brazed pipe jointing strategy.

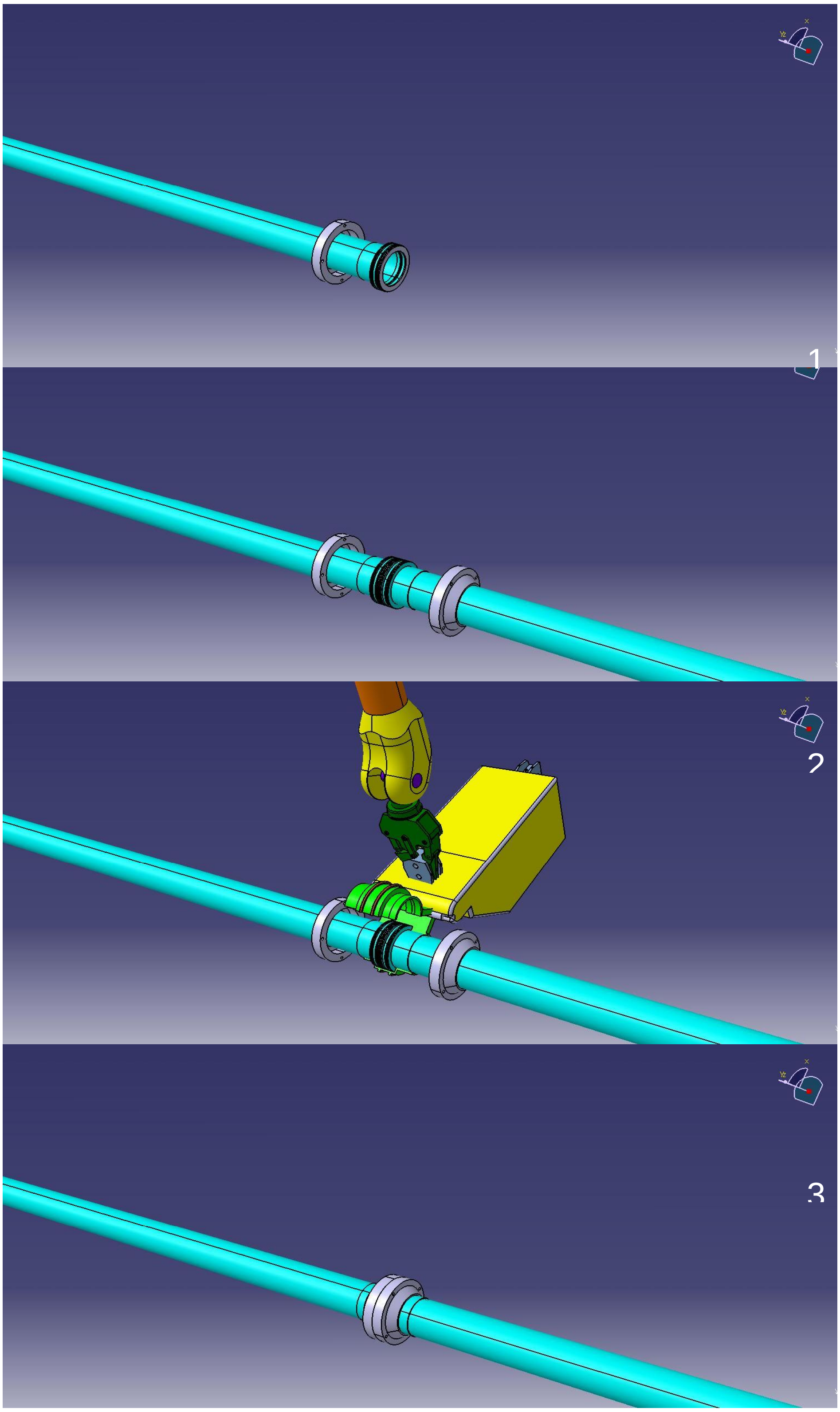


Figure 55: The brazed jointing process shown at successive stages – 1. Shows the fixed pipe end of the machine or plant. 2. Fixed pipe end and replacement component pipe end in place together. 3. Shows the multifunctional work-head positioned by a servo manipulator, 4. Is an illustration of how the finished joint might look following brazing.

5.4.2 Brazing Pipe Maintenance Tooling Inventory

1. Multipurpose work-head. A clamshell type inert atmosphere chamber with integral induction coil is proposed. The clamshell arrangement is clamped shut to form the inert gas enclosure, using either with a simple passive mechanical system or if access is poor a servo driven mechanism could be made.

As part of the induction system the work-head (transformer unit) illustrated in figure 54 has to be located close to the work coil. Joining/separating operations are effected by energising the work coil, the main power generator can be located more than 50 m away from the work area if necessary.

2. Alignment Tool. For fine adjustments to joint fit-up an alignment tool is necessary, see figure 54. As discussed in the previous chapter some misalignment can be tolerated by the joint. A BTS offers the advantage of completing the inert gas shielding by sealing off a localised area surrounding the joint. An external tool could be used given that the pipe system could be internally purged with inert gas.

3. Ultrasonic Inspection Device. As with welding this tool is used to inspect the quality of the joint following brazing.

4. Clamping tools. Simple bolting tools would be necessary to apply the clamping mechanism on the reinforcing flange, a V-band clamp or potentially an over-centre type mechanism could be used to suit RH capabilities.

5. Metrology tools. Special mechanical type tactile tool for inspection of joint fit up prior to brazing.

5.5 Cutting and Welding Pipe Maintenance Operations Task Description

Here an equivalent operations sequence to section 5.4 is described for welding and cutting based on the state of the art found in the literature and return of experience to form the basis for a comparison of their operational characteristics, benefits and drawbacks.

5.5.1 Sequence Description

The basic principles for a weld/cut pipe maintenance strategy for Divertor cooling are described in the State of the art section of this work, *Cooperative Maintenance Scheme for ITER Divertor cooling pipes*. Following careful reference to the experience gained at JET, the following procedure is proposed.

1. Pipe cutting begins by applying a clamping force or brace across the cut site. As with de-brazing this ensures any residual stresses present in the piping system are captured and can be relaxed in a controlled manner following cutting. Clamping/bracing can be applied by internal BTS or an external system depending on access conditions.
2. The cutting tool is then positioned at the cutting site using a location feature on the pipe. Cutting is performed away from the HAZ of the previous weld, allowing the subsequent re-weld to be made in fresh metal. Cut off material is collected using vacuum extraction ducts built into the cutting device. The cutting tool is then removed and the component is ready for disassembly.
3. The fixed pipe end is then inspected visually and using a dedicated mechanical tactile metrology device to ensure the cut off end is within tolerance necessary for refurbishment.
4. A jacking tool is then deployed to restore any distortion to the circularity of the pipe incurred either during service or cutting.

5. The cut face is then de-burred and the necessary edge preparation for re-welding such as bevelling or J type profiling is performed using a dedicated cutting tool. Again, refurbishment tooling includes built in vacuum extraction.
6. Geometric inspection of the finished pipe end is then performed using a dedicated mechanical tactile device.
7. The replacement component complete with insertion ring see figure 56 tack welded into place is then moved into the assembly position.
8. Alignment tooling is then used to fine position the pipe ends, making use of compliance in bellows or other convoluted elements in the pipe run. Inspection of joint fit-up prior to welding is then performed using a dedicated mechanical tactile device and/or visual feedback.

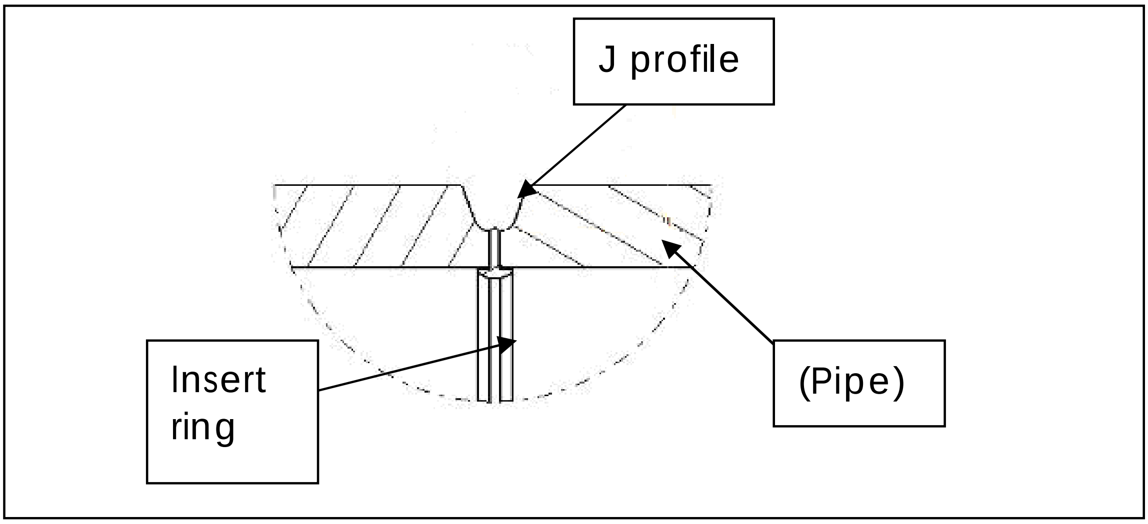


Figure 56: Insertion ring with J profile for improved weld penetration

9. The welding tool is then positioned at the joint, again making use of an alignment feature on the pipe run as with the cutting tool. Inert gas purging to prevent oxidisation and poor weld fusion is then initiated and the weld can be performed.
10. The weld tool is removed as well as the alignment tooling and a visual check is made of the finished joint.
11. NDT is then performed using US and He leak testing.

5.5.2 Cut/Weld Pipe Maintenance Tooling Inventory

The tooling for pipe maintenance is detailed in the ITER reference design. Again, the reference design lists only the minimum tools necessary for pipe cutting and welding. Should a failure occur, where pipes are damaged or welds fail, additional tooling will be necessary [Mills 1987]. This additional tooling is listed below.

1. ***Weld tool***
2. ***Cutting tool***
3. ***NDT weld inspection***
4. ***Alignment tool***

Minimum necessary tools as described in the State of the Art

5. ***Metrology tool - refurbishment:*** Mechanical tactile device for inspecting the refurbished, fixed pipe end.

6. ***Metrology tool - fit-up*:** Mechanical tactile devices for inspecting joint fit-up prior to welding.

7. ***Rounding Tool:*** Jacking type device for restoring pipe circularity.

8. ***De-burring/edge preparation tool:*** A de-burring tool is necessary to redress any irregularity in the cut edges prior to re-welding. Edge preparation such as bevelling or special J profiling can be made using the same tool.

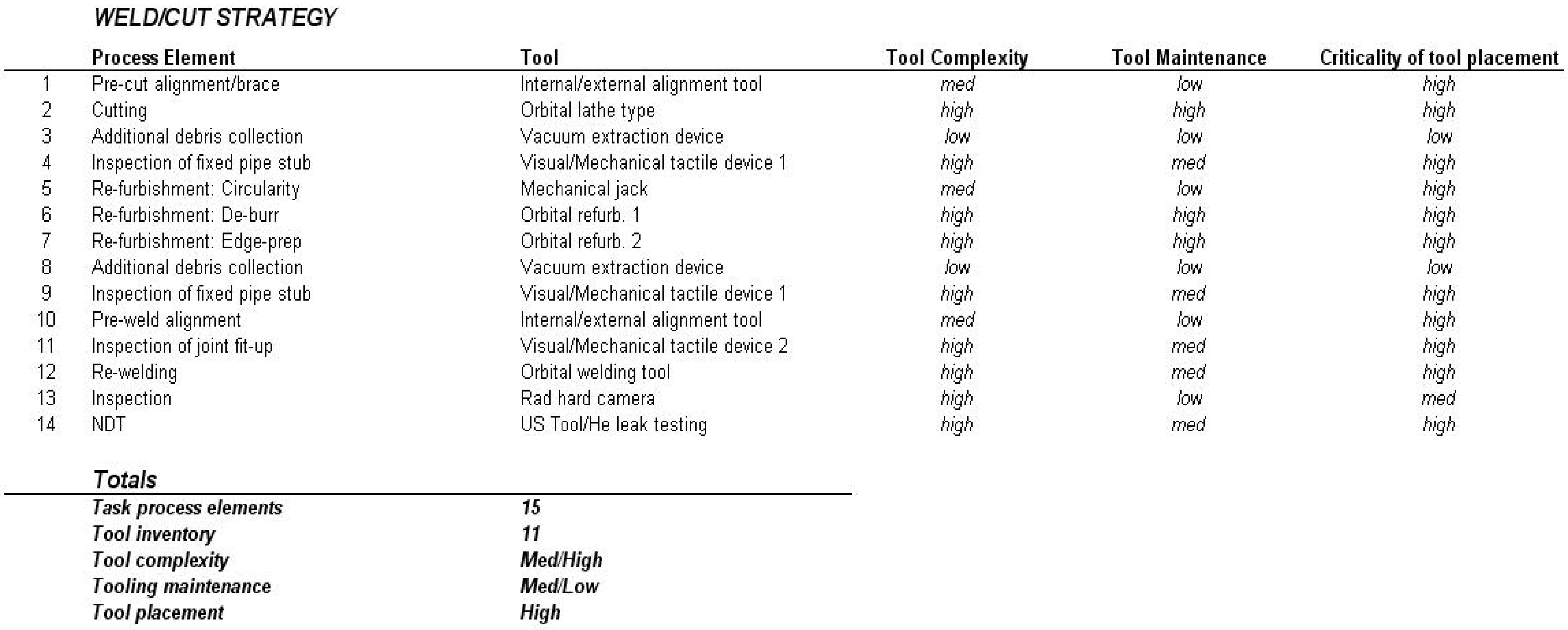
5.6 Comparison of Weld/Cut vs. Brazing Operational Feasibility

Considering tables 4 and 5 the brazed approach offers some unique operational benefits over the cut/weld approach. Fewer task sequence steps are necessary in the brazed approach in turn requiring fewer tools to complete them.

Significantly the orbital cutter, refurbishment tools and orbital welder are relatively complex devices with many moving parts and potential failure modes. Cutting tips have a finite life and must be regularly replaced. Induction heating by contrast is a solid state technology: the only moving parts in the multifunctional work-head are in the clamshell inert chamber: comprising of a simple passive hinge or servo driven depending on the application. Accurate alignment/placement is required for cutting, refurbishment, welding and joint fit-up in the case of welding, whereas brazing only requires accurate joint fit-up. Positioning of the multifunctional work-head is in principal not so critical. Heating is still achievable without great positional accuracy of the work coil, similarly perfect sealing of the inert chamber is not required to achieve a workable inert atmosphere. Cutting and refurbishment operations also have the inevitable risk of producing some contamination to the work area in the form of metallic swarf and debris. Furthermore it must be emphasised that material lost during cutting must somehow be made up in the subsequent re-assembly, either by making use of adjustment in bellows or by designing the replacement component to suit.

The concept design of the tooling and the definition of the operations sequence are valid contributions of this research to the field of Remote Handling. Furthermore the considered evaluation of the re-braze technique versus cutting and welding provides useful selection criteria for engineers and as such forms another contribution to the field.

Careful reference to the literature [Mills 1987], [Mills 1991] and the return of experience from JET shows that a more comprehensive suite of tooling is necessary than the bare minimum, *alignment, cutting, welding and weld inspection* presented in the state of the art. These additional tools are composed of metrology and refurbishment tools, listed in the comparison tables 4 & 5.



WELD/CUT STRATEGY

	Process Element	**Tool**	**Tool Complexity**	**Tool Maintenance**	**Criticality of tool placement**
1	Pre-cut alignment/brace	Internal/external alignment tool	*med*	*low*	*high*
2	Cutting	Orbital lathe type	*high*	*high*	*high*
3	Additional debris collection	Vacuum extraction device	*low*	*low*	*low*
4	Inspection of fixed pipe stub	Visual/Mechanical tactile device 1	*high*	*med*	*high*
5	Re-furbishment: Circularity	Mechanical jack	*med*	*low*	*high*
6	Re-furbishment: De-burr	Orbital refurb. 1	*high*	*high*	*high*
7	Re-furbishment: Edge-prep	Orbital refurb. 2	*high*	*high*	*high*
8	Additional debris collection	Vacuum extraction device	*low*	*low*	*low*
9	Inspection of fixed pipe stub	Visual/Mechanical tactile device 1	*high*	*med*	*high*
10	Pre-weld alignment	Internal/external alignment tool	*med*	*low*	*high*
11	Inspection of joint fit-up	Visual/Mechanical tactile device 2	*high*	*med*	*high*
12	Re-welding	Orbital welding tool	*high*	*med*	*high*
13	Inspection	Rad hard camera	*high*	*low*	*med*
14	NDT	US Tool/He leak testing	*high*	*med*	*high*

Totals	
Task process elements	***15***
Tool inventory	***11***
Tool complexity	***Med/High***
Tooling maintenance	***Med/Low***
Tool placement	***High***

Table 4: Summary of Weld/Cut operational characteristics

BRAZE STRATEGY

	Process Element	**Tool**	**Complexity of tool**	**Tool Maintenance**	**Criticality of tool placement**
1	Pre-braze alignment/brace	Internal/external alignment tool	*med*	*low*	high
2	Removal of reinforcing clamp	Bolting tool	*low*	*low*	low
3	De-brazing	Multifunctional Work-head	*med*	*low*	med
4	Alignment prior to re-braze	Internal/external alignment tool	*med*	*low*	high
5	Inspection of joint fit-up	Visual/Mechanical tactile device	*high*	*med*	high
6	Re-brazing	Multifunctional Work-head	*med*	*low*	med
7	Inspection	Rad hard camera	*med*	*low*	med
8	NDT	US tool/He leak testing	*high*	*med*	high

Totals

Task process elements	***8***
Tool inventory	***6***
Tool complexity	***Med***
Tooling maintenance	***Low***
Tool placement	***Med/High***

Table 5: Summary of braze operational characteristics

6 EXPERIMENTAL PROOF OF PRINCIPLES VALIDATION OF THE BRAZED JOINT

Having developed the brazed pipe jointing theory and demonstrated its operational benefits, in this chapter a trial of experimentation to validate the braze theory in terms of reversibility, leak tightness and structural quality is reported.

The first objective of the experimentation phase of this work was to validate the re-braze formulation used by Sandia. The practicality of applying this technique to the pipe joint designs detailed in chapter 2 was then assessed. A series of pressure and leak tests were then performed on joint samples. Destructive tensile testing was performed to determine the maximum load capacity of the brazed pipe joints. Further experimentation was made to determine whether increasing the time duration of heating at brazing temperature had any detrimental effects on the de-braze property.

6.1 Pilot Study – Reversibility Property

Prior to investing in the necessary experimental apparatus required to conduct a full re-braze trial, a pilot study made under a subcontracting arrangement was performed to assess general viability. With more than 25 years of experience in exotic material joining methods, brazing specialists Special Techniques Ltd of the UKAEA were selected to do the work.

Simple butt-type joints were fabricated again under a subcontracting arrangement by Duckworth and Kent Ltd, engineers of precision metalwork, see figure 57.

Figure 57: Pilot study pipe joint – Stainless Steel body (left) and Ni interface washer (right)

Each half of the joint consists of an OD Ø 30 mm, 1.5 wall thickness pipe section with flange, produced as one piece from AISI 316L Stainless Steel material. A ¼” BSP female interface was machined into the opposite end to the flange on each sample for subsequent pressure and leak testing. 2 mm thick interface washers were machined from Ni-200 material.

The Ni-200 interface washers were brazed to the Stainless Steel flanges using a high temperature Ni based braze material Ni70.9 Cr19 Si10.1. Brazements were made at 1040 ˚C for 3 minutes using a 200 kW Torvac T200 vacuum furnace. The temperature was raised at a rate of 10 ˚C/min.

The flange/interface washer assemblies were then brazed together with the lower temperature Au82Ni18 braze material, completing the joint assembly. Brazements were made at 1000 ˚C for 5 minutes, the temperature was raised at a rate of 10 ˚C/min. The assembled pipe joints were then leak tested using the Leybold XL340 leak detector. A maximum leak rate of 1 x 10^{-9} Pa•m^3•sec^{-1} was detected.

Debrazing was then attempted using the same vacuum furnace, at 1040 ˚C for 5 minutes, temperature again was raised at a rate of 10 ˚C/min. Parts were hung from the ceiling of the furnace and loaded with 300 g of weights to aid separation.

Special Techniques were unable to separate the joints under these conditions. Two further attempts were made with an increased weight of 0.5 kg and incremental increases of temperature of 30 degrees. The results of de-brazing were negative, joints remained intact.

Two possible reasons for the negative results were proposed; the heating cycle being too long overall and insufficient loading during de-brazing. The vacuum furnace was selected as the method of heating as it offers the lowest risk of oxidation contamination compared to flux or inert gas brazing. A long temperature cycle was required to raise the furnace to the necessary brazing temperature which may have resulted in some diffusion bonding resulting in homogeneity in the joint and ultimately the inability to separate. Due to the small dimensions of the furnace there was a limitation to the amount of loading that could be applied to the assemblies; loads of greater than 0.5 kg were not possible. Also the addition of a twisting force to shear the surface tension of the liquid braze was not possible.

6.2 Full Re-Braze Trial

Following the results of the pilot study it became clear that incremental changes to joining parameters would have to be made iteratively in order to fully research the re-braze technique. A workshop and laboratory space was created, dedicated to the fabrication of test parts, brazing operations and pressure testing. This section presents the laboratory equipment used, the design of the test parts and the tests performed.

6.2.1 Experimental Set-Up

Having selected induction brazing as the most amenable to RH methods, a 10 kW solid state induction heating system was used for experimentation, see figure 58. The induction system includes a controller with temperature feedback via high temperature K-type Inconel thermocouple. A handheld Oxygen monitor was used to measure the atmosphere surrounding the braze. A 95% Ar 5% H inert gas mix was used to purge the braze area.

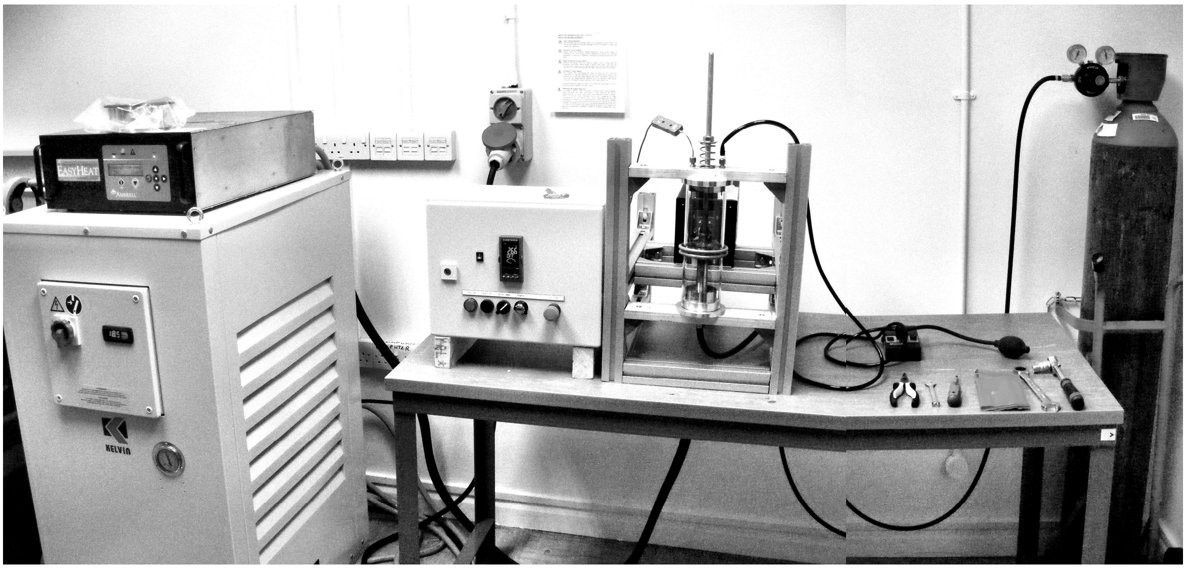


Figure 58: General experimental set-up

A dedicated braze test rig was built see figure 59 to support the inert gas chamber. A Pyrex cylinder was used to form the inert chamber sealed at each end with turned Aluminium end-caps. A positioning rod was used to apply axial and torsional loads to the test pieces during de-brazing. Beam bending calculations were made to ensure the structure of the test-rig was capable of supporting a 100 kg pulling force during de-brazing. A separating pre-load was applied to the positioning rod during de-brazing using compression springs. The universal Aluminium beams used for construction allowed for position adjustment of the inert chamber and work-head and coil, seated behind the chamber.

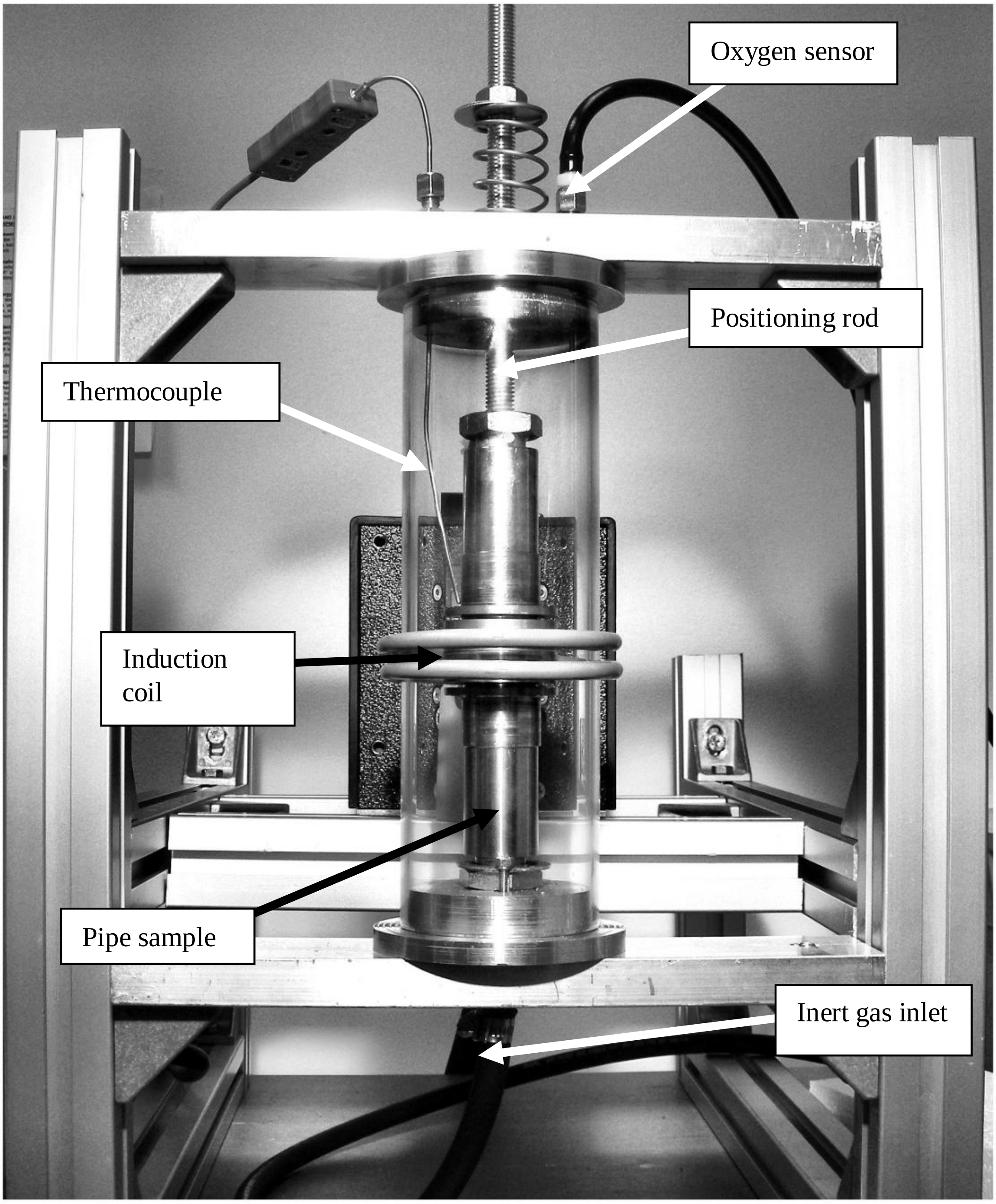


Figure 59: Braze test rig

Inert gas enters at the bottom of the chamber and flows inside the test piece, the opposite end of the test piece is open allowing the gas to purge the remainder of the chamber. The Oxygen monitor probe is located at the top of the chamber.

A high pressure hand pump was used to perform pressure testing. A mechanical dial gauge was used to note test pressures.

6.2.2 Braze Wettability Tests

Wettability tests were performed for Ni-200 base material and Au82 Ni18 braze alloy. A machined surface of the Ni material was positioned inside the inert chamber and covered in samples of the braze alloy. Good adhesion and low contact angle was observed following heating see figure 60**.**

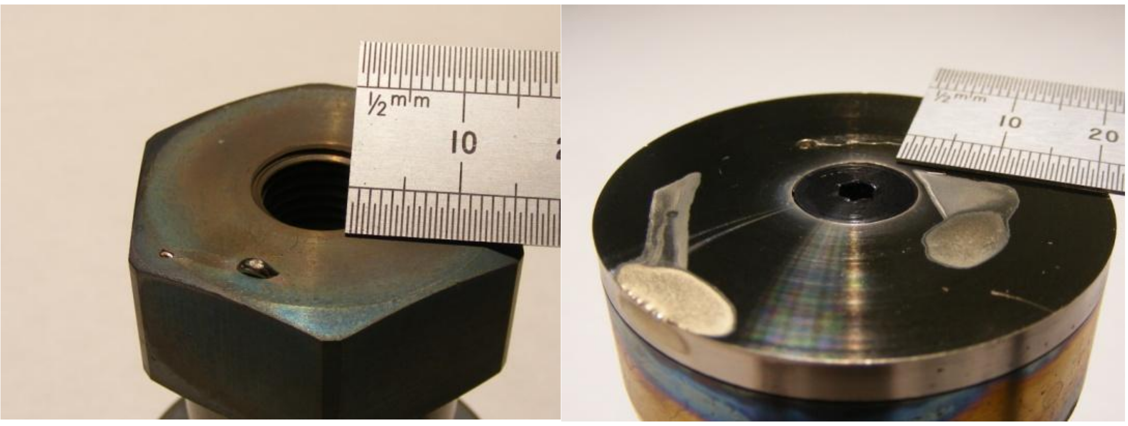


Figure 60: Wettability study

6.2.3 Preparation of Test Parts

Test pieces for the simple butt and reinforced type pipe joints were turned from AISI 316L Stainless Steel. A ½" BSP female hydraulic connection was machined into each part for subsequent pressure testing. For the simple butt type samples consisted of a 50 mm long, Ø30 mm OD, 1.5 mm wall thickness pipe section with a flanged face of 3 times the pipe wall thickness see figure 61.

Figure 61: Simple butt-type test piece

The design used for the reinforced joint consists of a one-piece pipe and flexible element section with a separate reinforcing flange, see figure 62 and 63.

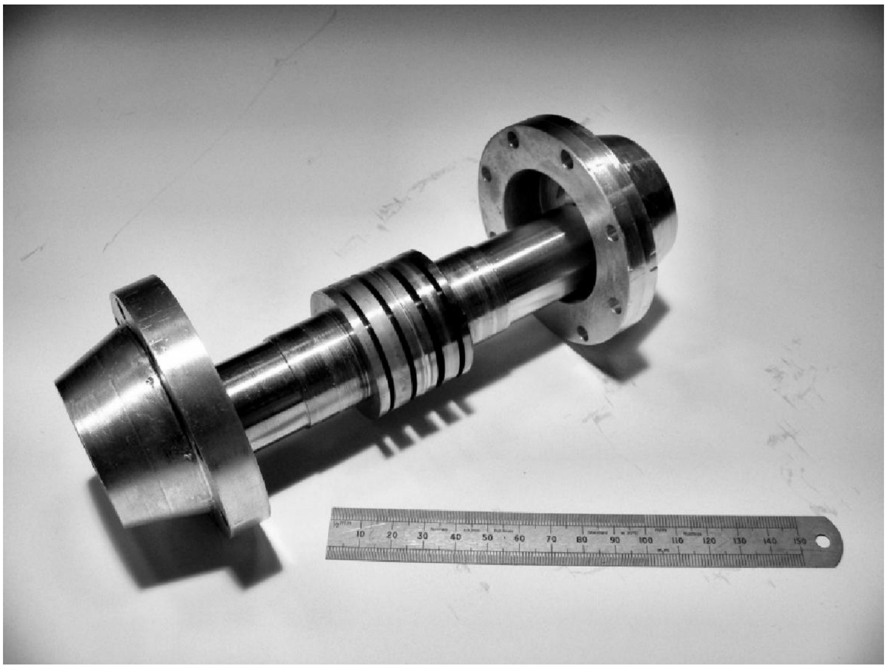


Figure 62: Load segregated joint

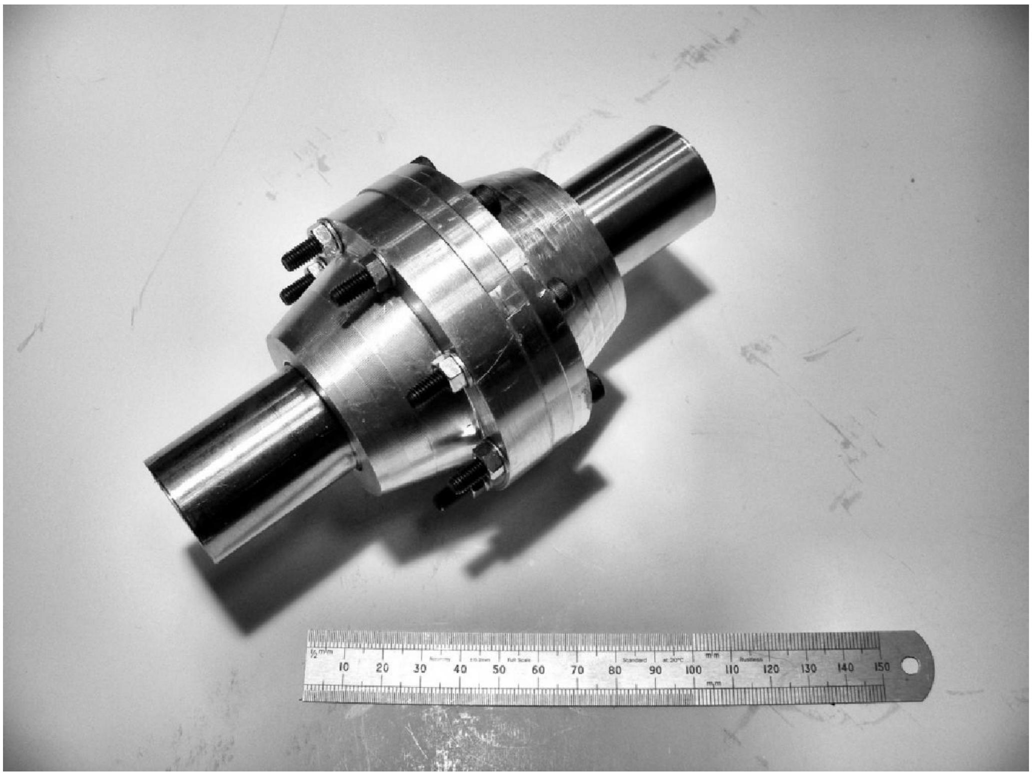


Figure 63: Load segregated joint (assembled)

The pipe section was as that for the simple butt joint design. The flexible element was formed by 2 external and 1 internal 8 mm deep grooves for each flange half. Corresponding Ni washers were fabricated and permanently joined to the Stainless Steel components by an electron beam weld made using a Torevac 8 kW machine. Welding was performed at 10 mA current at a speed of 12 mm/s with the aim of producing 1.5 mm of weld penetration. Braze preforms were cut from 0.05 mm thick Au82 Ni18 foil. Completed parts were then cleaned with alkaline based cleaner.

6.2.4 Re-Braze Testing

Joints were heated to a temperature of 940 ^{o}C over a period of 1 min 20 sec, see figure 64. This temperature was then maintained for a period of 10 seconds to ‘heat-soak’ the parts prior to raising them into the liquidus of Au82Ni18 at 955 ^{o}C**.** The temperature was then raised to 960 ^{o}C for brazing, slightly above the filler liquidus to allow for potential errors in the temperature feedback arrangement. Again this temperature was maintained for 10 seconds and a visual feedback of braze alloy melting was observed. This temperature/time profile was created using advice from the manufacturer of the braze material and with due consultation of the literature, [Schwartz 2003].

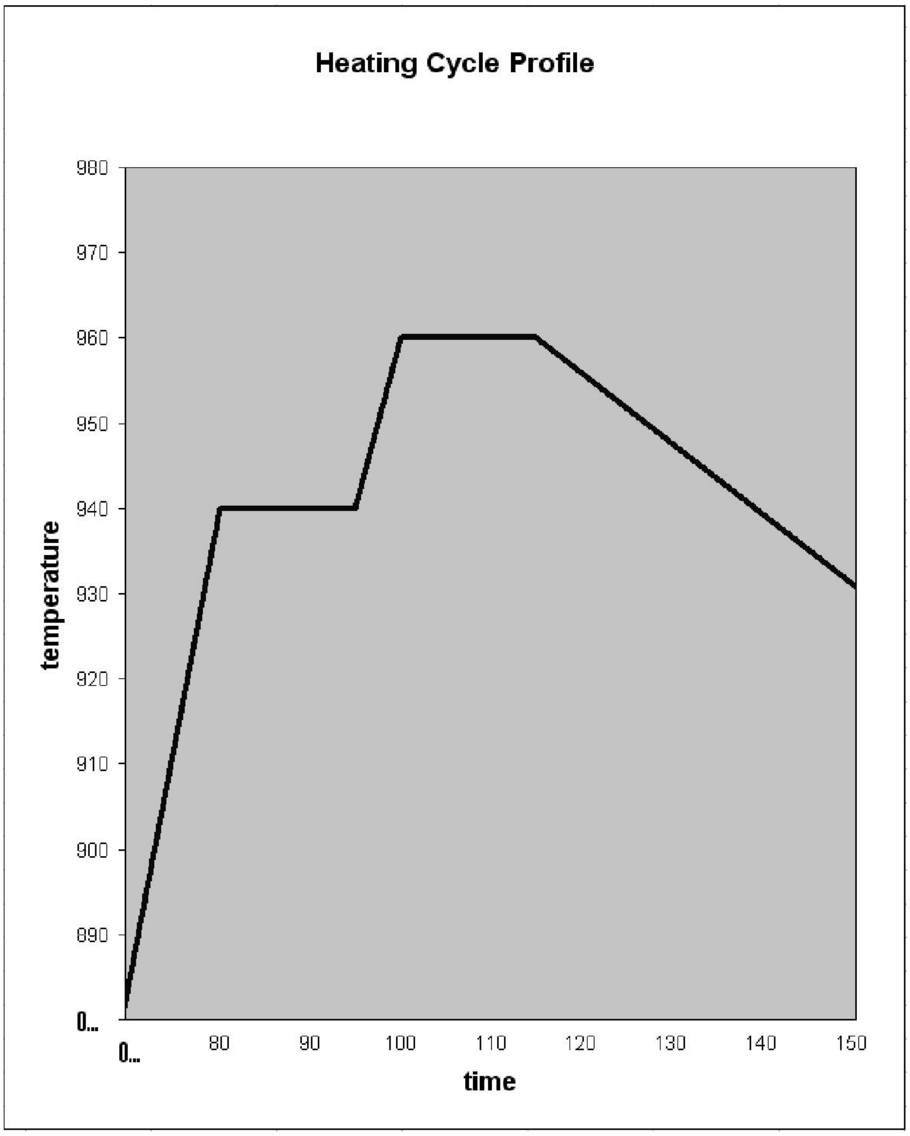
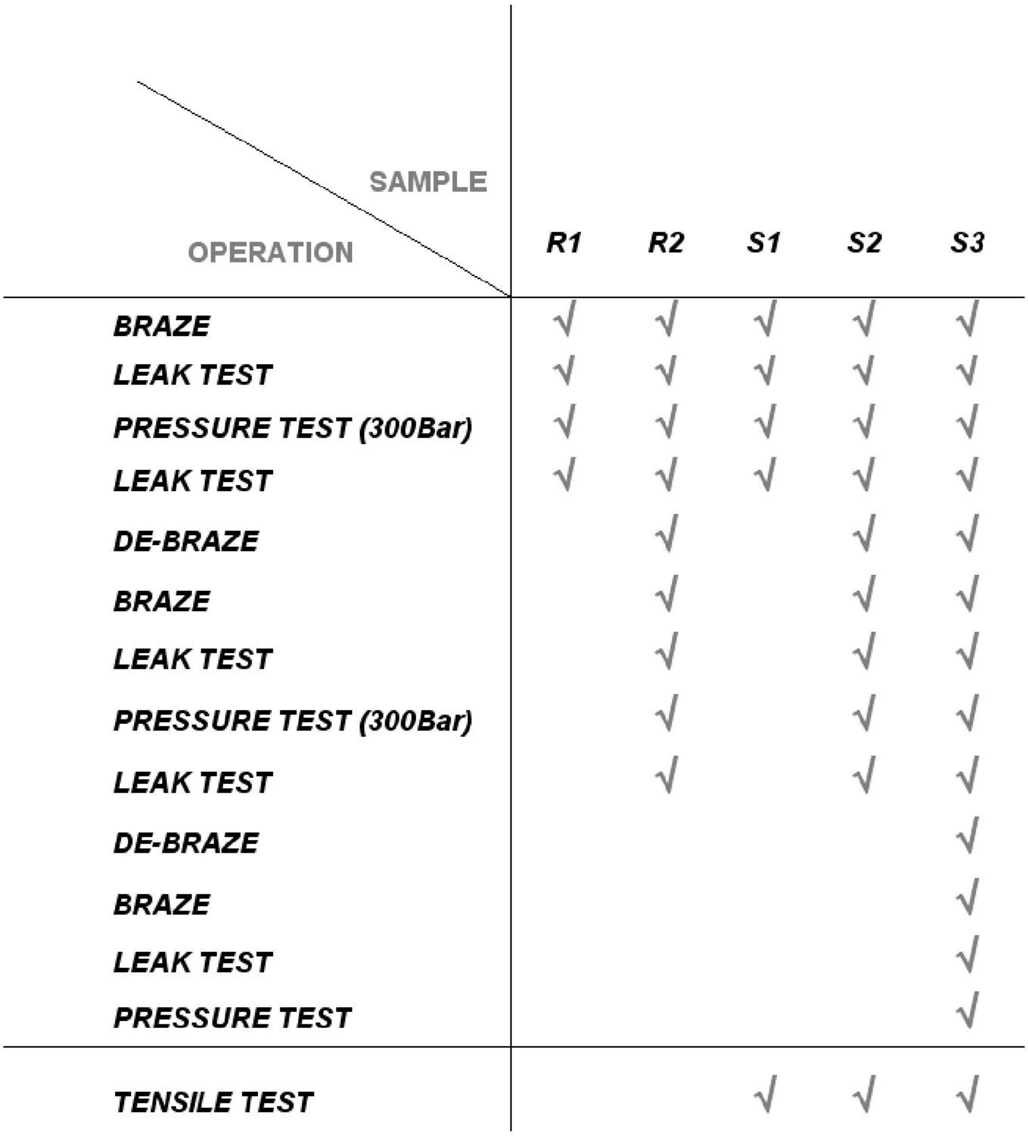


Figure 64: Heating profile

Brazed assemblies were made under their own weight; no additional compressive force was used. An Oxygen level of better than 0.05 % was achieved during brazing operations. Following brazing, assembled joints were leak tested again using the Leybold XL340 leak detector. A maximum leak rate of 1 x 10^{-9} Pa•m^3•sec^{-1} was detected for all assemblies used, this is within the range acceptable for in vessel components for ITER. Joints were then pressure tested at 30 MPa for 5 seconds and re-tested for leaks. No degradation of leak tightness was found.

De-brazing proved successful. The same heating profile of heat and dwell that was used for joining was used for the de-braze. Low separation forces were necessary; for normal operations a force of 15 N was applied. Forces as low as 7 N still proved effective.

3 samples of the simple butt type joint were prepared and 2 of the reinforced type. Table 6 covers the tests performed.



SAMPLE / OPERATION	R1	R2	S1	S2	S3
BRAZE	√	√	√	√	√
LEAK TEST	√	√	√	√	√
PRESSURE TEST (300Bar)	√	√	√	√	√
LEAK TEST	√	√	√	√	√
DE-BRAZE		√		√	√
BRAZE		√		√	√
LEAK TEST		√		√	√
PRESSURE TEST (300Bar)		√		√	√
LEAK TEST		√		√	√
DE-BRAZE					√
BRAZE					√
LEAK TEST					√
PRESSURE TEST					√
TENSILE TEST			√	√	√

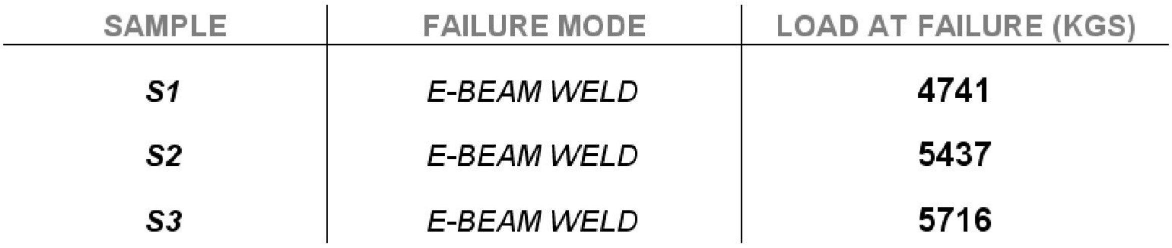
Table 6: De-brazing tests

Standard butt-type joint samples were retained after each stage of testing as detailed in table 6.

Of the first batch of brazed assemblies one of the simple butt type joints failed the initial leak test. The joint was de-brazed then re-brazed with a longer dwell time at brazing temperature of 20 seconds, the joint subsequently passed leak testing and was serviceable for the remainder of testing.

6.2.5 Destructive Tensile Testing

The three samples S1 to S3 indicated on table 6 were destructively tensile tested using an AJT Ltd model 175V tensile testing machine with maximum capacity of 50 t. The results are presented in table 7.



SAMPLE	FAILURE MODE	LOAD AT FAILURE (KGS)
S1	*E-BEAM WELD*	**4741**
S2	*E-BEAM WELD*	**5437**
S3	*E-BEAM WELD*	**5716**

Table 7: Tensile testing results

All samples failed in the weld joining the Ni interface washer to the Stainless Steel body of the pipe figure 65 – the braze remained intact in all samples.

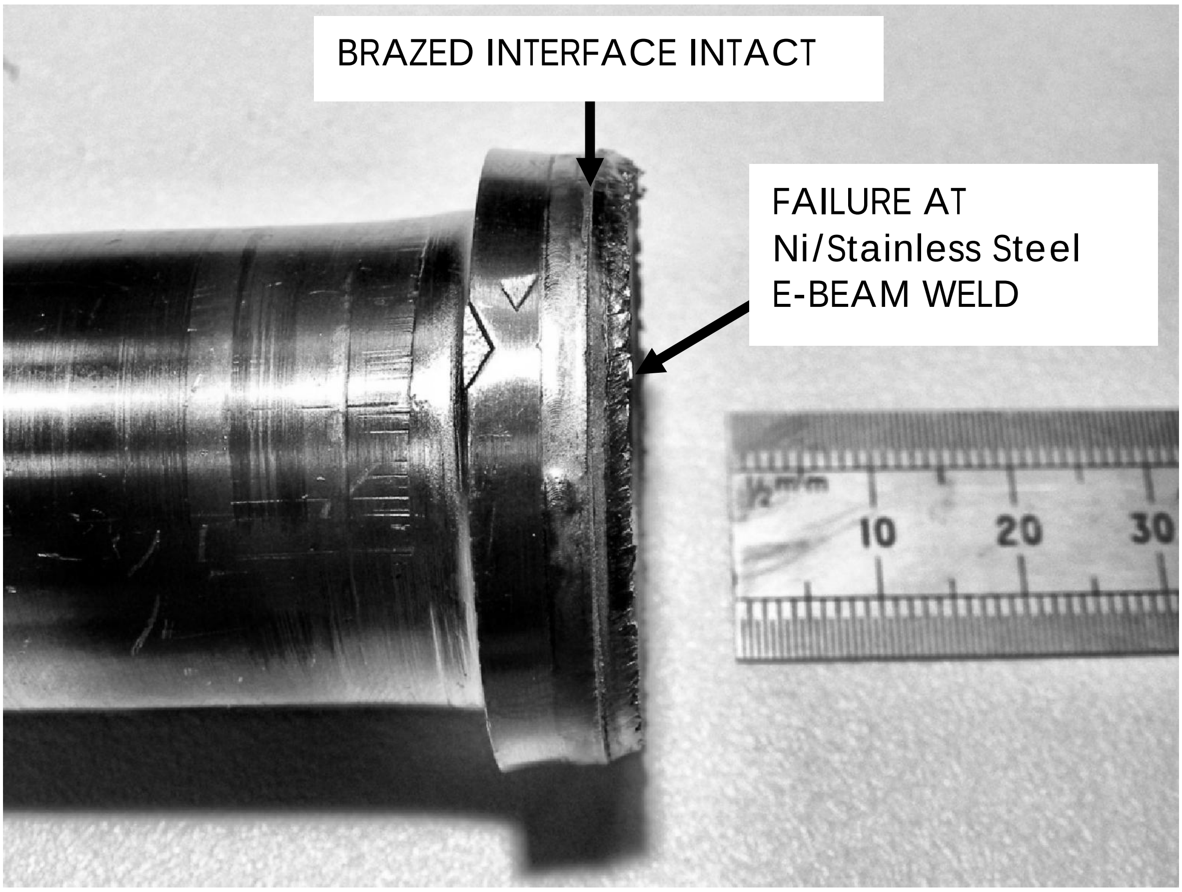


Figure 65: Simple butt joint following tensile testing – brazed interface remains intact, failure occurred in the Stainless Steel /Ni electron beam weld

6.2.6 Prolonged Brazing Temperature Trials

A series of tests were performed to investigate the effects of increased time at brazing temperature on the reversibility property. 10 seconds at brazing temperature was found to be adequate for creating a structurally sound, leak proof joint during re-braze testing. Tests were performed on a straight butt type joint (non pipe joint) as that used for wettability tests. The joining surfaces were refurbished on the lathe between each brazing operation. Time at brazing temperature was increased to 30 s, 1 min, 2 min, 3 min and 5 min. A 10 second pre-brazing temperature dwell period at 940 ^{o}C was used for each operation. No deterioration in the de-brazing property was detected.

7 DISCUSSION

In this chapter the results of this research are summarised and considered in the context of ITER type RH operations. Deficiencies in the experimentation are detailed and future work is outlined.

7.1 Summary of Results

The basic principles for a RH UHV pipe jointing method based on a reversible brazing technique have been developed in this work. The re-braze technique as set out by Sandia National Laboratories has been independently verified. Joints can be brazed and de-brazed multiple times in a fluxless inert gas environment using heating by electromagnetic induction.

Two types of pipe joint have been designed and tested; one basic butt type joint and one reinforced type. Each variant has proven to be leak tight and capable of tolerating 30 MPa of internal pressure, both after the initial braze and repeated re-brazing. The operating pressure for Divertor cooling pipes for example is 4.2 MPa, this means a comfortable safety factor of greater than 6 could be achieved using the brazed joint. Significantly these results were obtained without performing any cleaning or refurbishment of the brazed joint prior to re-brazing. The avoidance of refurbishment operations is particularly attractive from a RH operations perspective as the necessary tooling can potentially be eliminated.

Other UHV pipe jointing technologies are available in the field of RH such as compression seal flanges and cutting and welding. The re-braze approach offers some unique operational advantages. Flanges with compression seals are simple to disassemble, however the joint is not as strong as the surrounding material and therefore represents an expected failure point. Brazing by comparison is substantially as strong as the material being joined. Welded joints have similar structural properties to brazing but disassembly can only be achieved by a mechanical cut. Brazing requires fewer, less sophisticated tools than the weld/cut approach. Crucially the brazed approach offers a clear competitive advantage over welding in terms of ease of disassembly. This combined with the avoidance of contamination by cut-off material and a higher number of potential re-joins leads to the conclusion that brazing represents a lower risk of RH operational failure than the weld/cut strategy. Further work is necessary to determine whether the brazed approach can offer the same reliability as welding in service.

7.2 Structural Properties of the Braze Joint

The aim for the project was to create a reversible UHV joint with structural properties approaching that of a welded joint. The strength of a welded joint for the pipe geometry used for the tensile tests performed in this work can be calculated, working with the assumption that the weld is as strong as the parent materials being joined. For a Stainless Steel pipe the failure load is proportional to the Ultimate Tensile Strength (UTS) and the cross-sectional area of the pipe.

The failure load for a welded joint for the pipe (30x1.5 AISI 316L) is calculated to be 63.1 kN. That the tensile testing samples failed in the e-beam weld between 46.5 kN and 56 kN with the braze intact shows that the braze has at least this loading capacity, not far from that calculated for a welded joint.

The reason the e-beam weld failed at a lower load value than that calculated may have been down to poor weld penetration. Close examination of the samples returned from tensile testing show weld penetration of approximately 1.2 mm at the fracture point as opposed to the 1.5 mm originally specified for the joint, see figure 66.

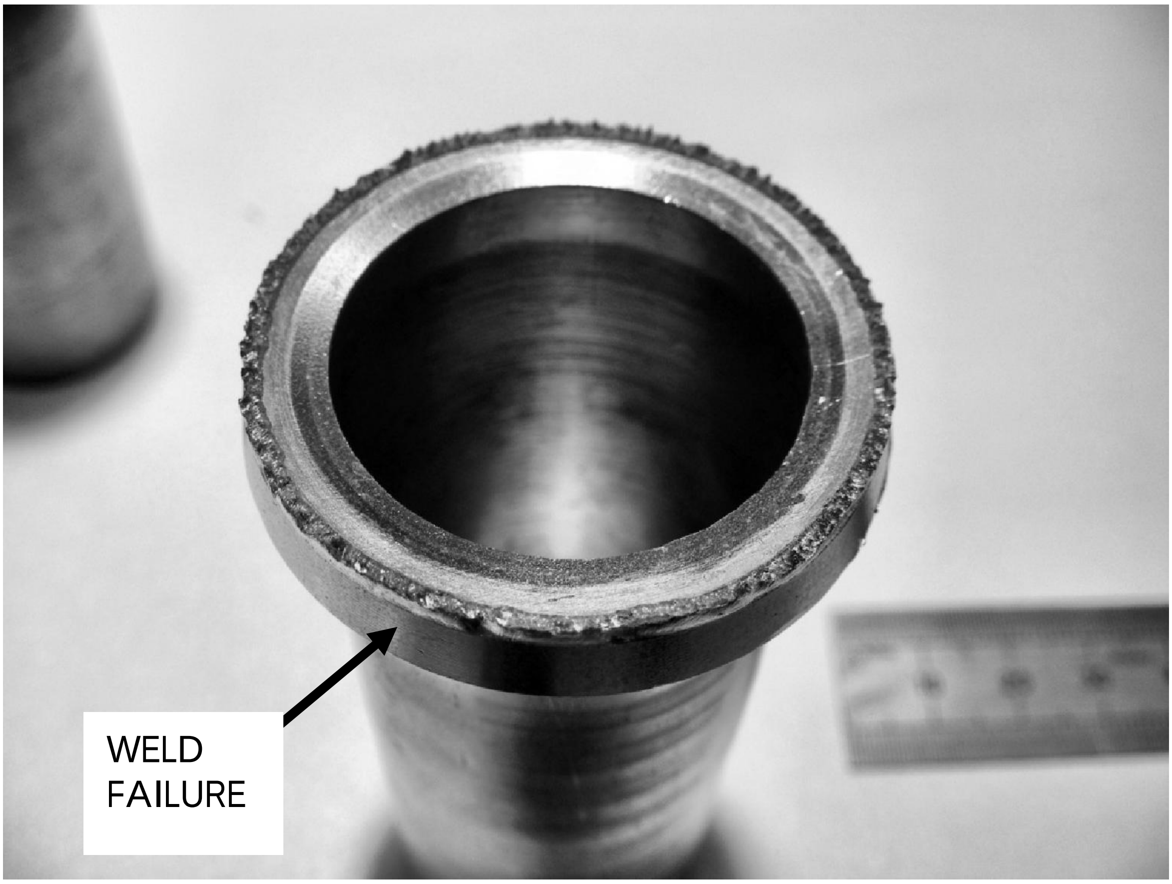


Figure 66: Sample following tensile testing – the failed electron beam weld is indicted with 1.2 mm penetration

7.3 The Reinforced Joint

The reinforced joint was designed partially on the assumption that the brazed interface represents the most likely failure mode of the system. From the results of tensile testing it would appear that this may not be the case. However future structural testing such as bending for example may yield contrasting results. Bending particularly may induce a ‘peel’ scenario whereby small inconsistencies in braze penetration could propagate into cracks as discussed in Chapter 2.

The reinforced joint design has advantages other than the potential for improved strength. The flexible elements assist with alignment, crucial for the close tolerances necessary for brazing. The testing work performed so far on this design shows it to be both leak tight and capable of tolerating internal pressure well in excess of those required for ITER.

7.4 Brazing Cleanliness and Accurate Fit-Up

Cleanliness and joint fit-up are crucial parameters for brazing. The flexible stress regulating element and reinforcing flange have the additional function of helping to accommodate some degree of angular-axial and/or axial misalignment. For a flexible element of 0.75 mm wall thickness practical deflections can be made with low clamping forces of 650 N. This level of force is practical using RH methods; alignment forces of this magnitude were achieved at JET, in addition the alignment tool for the reference design for ITER pipe maintenance, *Cooperative Pipe Maintenance Scheme* is specified at 2000 N axial alignment force. The oversized flange area on mating surfaces serves to ease the alignment as discussed in Chapter 2. Further study is necessary to demonstrate the alignment property of the flexible element. This work should include brazements made from misaligned samples and subjected to in-service structural testing to demonstrate fitness for purpose.

In order to promote full distribution of the braze filler across the brazed joint and good resultant joint strength joining surfaces must be free of contamination such as oxidation, grease, residues and films etc. Depending on the application, braze components are typically cleaned with solvents or alkaline solution prior to brazing. During first assembly of the ITER machine manual intervention will be permissible allowing thorough cleaning to be performed. For subsequent re-joins the ultra-clean conditions demanded for tokomak operation may negate the need to re-clean prior to re-brazing. A protective cap for the fixed braze interface would help protect from potential contamination. For the replacement component conditions inside the Hot-Cell will permit the necessary inspection and cleaning.

7.5 Brazing Temperature Duration Tolerance

The tests performed on prolonging the brazing temperature duration show that there is a comfortable degree of tolerance over and above the minimum time necessary to create a reversible braze where no permanent joining occurs. This tolerance is clearly attractive from an operations point of view as it shows that small variations in heating parameters such as coil positioning heating time can be tolerated. In addition longer heating cycles (up to 30 seconds) were necessary during some re-brazing operations to melt down localised build-ups of residual braze material found at the joint interface. Longer heating cycles such as these can be safely performed without degrading the de-braze property.

7.6 Radiation Tolerance

For the Divertor cooling pipes the brazed joint would be required to tolerate a neutron loading of 0.5 W/cm^2. Neutron irradiation can cause materials to transmute, any products of this process must be compatible with tokamak operation. Au transmutes to Mg posing a contamination risk raising some doubt over the suitability of the re-braze formulation used in this work. The effects of Silver transmutation have been studied [Peacock 1996] and a very small proportion of the Ag was found to have transmuted, furthermore, only a fraction of the Cd produced could be effectively vaporized under vacuum conditions. The issue of transmutation was raised at ITER as brazing is a likely technology for assembling PFCs. The effects of transmutation in this environment would be at their highest. For other applications in well shielded areas such as Divertor cooling pipes, the reduced effect of transmutation may make the use of Au Ag acceptable. Furthermore for ex-vessel and Hot-Cell applications transmutation would not be the same concern as in vessel. Regarding radiation tolerancing of RH equipment for the brazed approach, induction heating equipment has good potential for rad-hardening for RH purposes as discussed in Chapter 2.

7.7 Future Work

7.7.1 In Service Qualification

Welding is a proven industrial standard with abundant data available in the literature on a wide range of applications. As such welding is an attractive option from the perspective of reliability in service. Conversely little data is available on specific braze formulations and their many uses. A comprehensive testing campaign is necessary to qualify the brazed joint for in service conditions. Prolonged cyclic tensile, shear, bending and torsional loading should be performed on samples. Temperature and internal pressure variation should be applied during these tests. Subjection to Neutron irradiation prior to this stimulation should also be performed. Samples should be leak tested then sectioned and submitted for micrographic analysis to inspect the quality of the braze interface.

7.7.2 RH Procedure Qualification

One aim of RH procedure qualification would be to converge on a standard heating cycle reliable under both first braze and re-braze conditions (including melting localised build-ups of residual braze material). The heating cycle should also be designed to tolerate some variation in tool positioning within predetermined limits. Should an effective standard cycle be found, temperature feedback and power control would not be necessary and could be eliminated from the tooling for added simplification.

In this work re-brazing was performed following separation as soon as the joint had cooled sufficiently to open the inert chamber and place a new braze foil without oxidation occurring. Temperatures less than 200 ˚C were found to be acceptable to perform the braze foil replacement taking approximately 15 minutes to cool to this level. For full RH applications it is conceivable that the fixed pipe end will remain exposed to shut-down conditions for much greater lengths of time before a subsequent re-braze is performed. Further study is necessary to determine whether oxidation becomes problematic to the degree that refurbishment is required.

Depending on the results of qualification trials, it may be necessary to design some additional tools for recovery from failure scenarios. This would include a cutting tool to break the brazed joint by destructive methods. A refurbishment tool may be necessary if some damage to the joint interface occurs. If the fixed flange section became irrecoverably damaged a further cutting and re-welding suite of tooling would be necessary for recovery from this failure scenario.

7.8 Contributions to the Field of Remote Handling

The results of this research make a valuable contribution to the field of Remote Handling summarised as follows:

1. A novel concept for Remote Handling pipe jointing tooling designed for ease of disassembly is proposed.
2. A novel structurally reinforced re-braze pipe joint has also been designed and tested.
3. Proof of principals validation of the theory developed in this research has been made:
    - Brazing trial, validation of the re-braze technique.
    - Structural analysis, including tensile and pressure testing of the joint.
4. The operational advantages of the re-brazing technique over conventional welding and cutting methods have been qualitatively shown.
5. Detailed information, beyond what is available in the literature, is made available on RH welding cutting techniques is presented.

Together the achievements listed above form the case for a novel remote pipe jointing technology, more reliable, faster and with fewer inherent risks of operational failure than the state of the art *cutting and welding.* Initial results show the brazing technique can compete with welding in terms of structural quality. With disassembly vastly simplified in the brazing technique, there is the possibility to gain a clear competitive edge over *cutting and welding* opening up great potential for application areas well beyond the bounds of remote handling in magnetic confinement fusion power research.

This research benefits greatly by the work carried out at Sandia National Laboratories on de-braze theory. Some valuable additions to this technique are detailed in this thesis; including an independent validation of the Sandia theory and in addition to this the first results of tensile testing on de-braze type joints along with detailed information on how to adapt the technique to UHV pipe jointing applications.

8 CONCLUSIONS

The basic principles for a RH UHV pipe jointing technique designed for ease of disassembly have been developed and proven in this work. Pipe joints can be brazed and subsequently de-brazed using electromagnetic induction heating in an inert gas environment. The brazed joint is capable of sustaining an internal pressure of 30 MPa and is leak tight to UHV standard (maximum 1 x 10^{-9} Pa•m^3•sec^{-1}). Under axial loading the brazed joint was found to have tensile strength at least equal to that of a welded joint (>54 kN failure load for a Ø30 mm OD, 1.5 mm wall thickness pipe). Furthermore these properties are consistently achievable following multiple braze/de-braze operations. No cleaning or refurbishment was performed between re-braze operations.

These results show that brazed pipe joints with similar structural properties to welded joints can be made. The brazed joint has the distinct advantage that it can be disassembled with the simple addition of heat, whereas the welded joint has to be cut.

A reinforced joint designed to shield the brazed interface from the in service joint loading conditions has been designed and tested. The reinforced joint features a compliant element designed to assist with the accurate alignment necessary to make brazements.

The proposed brazing technique offers real benefits for RH pipe maintenance operations in terms of cost, time and risk reductions. Following careful reference to RH operations experience at JET, operational procedures were outlined for both the re-braze technique and the state of the art, *cutting and welding* in the context of a pipe maintenance scenario. These were then compared looking at parameters such as number of task sequence steps, number of tools required and complexity of tooling. Due principally to the avoidance of mechanical cutting and the necessary refurbishment required prior to re-welding, the brazed approach requires fewer sequence steps, fewer tools and represents a more attractive pipe jointing solution.

The principal contributions this research makes to the field of Remote Handling are as follows:

- Conceptual design for novel Remote Handling pipe jointing tooling designed for ease of disassembly
- Design of a UHV pipe joint capable of exploiting the de-braze technique is presented
- Independent proof of principals validation of the de-braze technique, of great interest to the Remote Handling engineer for disassembly and assembly of high value plant and components
- The first formal structural analysis of the de-braze joint, pressure and tensile testing
- Creation of a Remote Handling operations sequence for de-braze pipe jointing using the tooling concept
- Evaluation of the operational benefits of de-braze pipe jointing for Remote Handling
- Detailed information on available RH welding and cutting techniques, previously unpublished.

The complications of disassembling piping systems where welding has been used are clearly not limited to the bounds of magnetic confinement fusion research. The brazed technique possesses a clear competitive advantage over welding and cutting with respect to ease of disassembly. Subject to further qualification work, the brazed pipe maintenance technique could generate broad appeal across many industry sectors.

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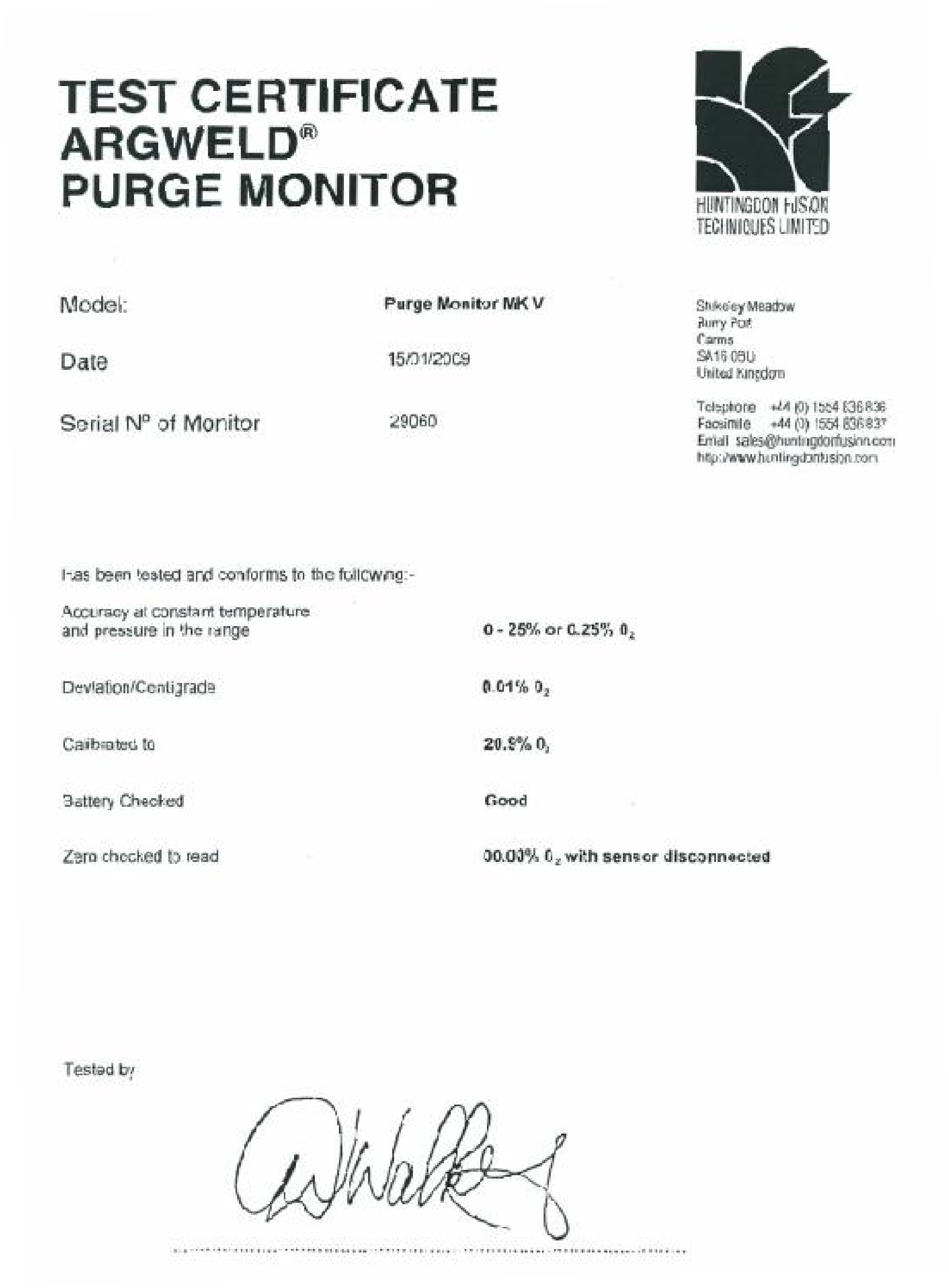
APPENDIX A – Experimental Apparatus Specifications

Oxygen Monitor



TEST CERTIFICATE ARGWELD® PURGE MONITOR

HUNTINGDON FUSION TECHNIQUES LIMITED

Stukeley Meadow
Burry Port
Carms
SA16 0BU
United Kingdom

Telephone +44 (0) 1554 836 836
Facsimile +44 (0) 1554 836 837
Email sales@huntingdonfusion.com
http://www.huntingdonfusion.com

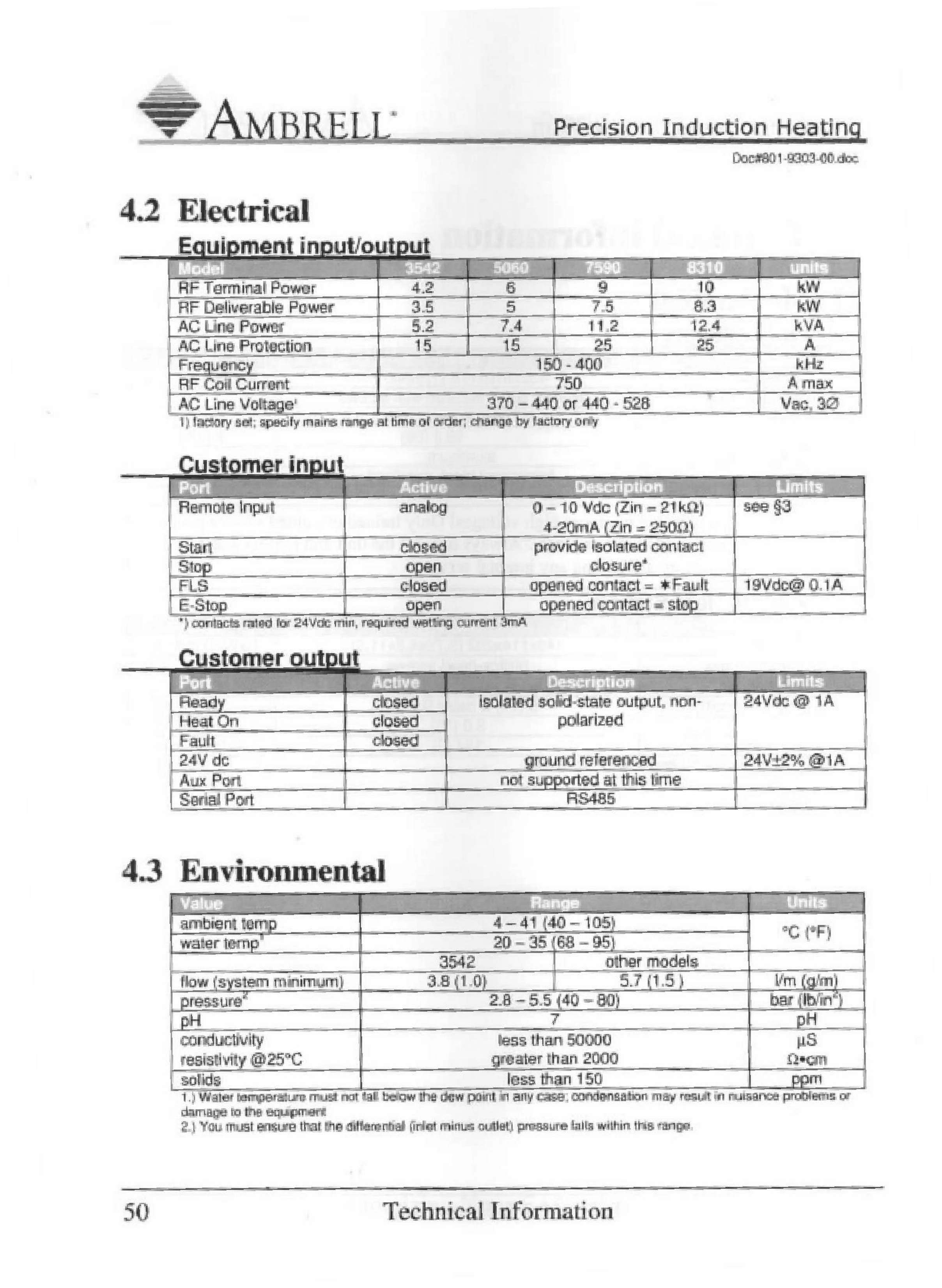
Model:	**Purge Monitor MK V**
Date	15/01/2009
Serial Nº of Monitor	29060

Has been tested and conforms to the following:-

Accuracy at constant temperature and pressure in the range	**0 - 25% or 0.25% O_2**
Deviation/Centigrade	**0.01% O_2**
Calibrated to	**20.9% O_2**
Battery Checked	**Good**
Zero checked to read	**00.00% O_2 with sensor disconnected**

Tested by

Induction Heater



AMBRELL® Precision Induction Heating

Doc#801-9303-00.doc

4.2 Electrical

Equipment input/output

Model	3542	5060	7590	8310	units
RF Terminal Power	4.2	6	9	10	kW
RF Deliverable Power	3.5	5	7.5	8.3	kW
AC Line Power	5.2	7.4	11.2	12.4	kVA
AC Line Protection	15	15	25	25	A
Frequency	150 - 400				kHz
RF Coil Current	750				A max
AC Line Voltage[1]	370 – 440 or 440 - 528				Vac, 3∅

1) factory set; specify mains range at time of order; change by factory only

Customer input

Port	Active	Description	Limits
Remote Input	analog	0 – 10 Vdc (Zin = 21kΩ) 4-20mA (Zin = 250Ω)	see §3
Start	closed	provide isolated contact closure*	
Stop	open		
FLS	closed	opened contact = ∗Fault	19Vdc@ 0.1A
E-Stop	open	opened contact = stop	

*) contacts rated for 24Vdc min, required wetting current 3mA

Customer output

Port	Active	Description	Limits
Ready	closed	isolated solid-state output, non-polarized	24Vdc @ 1A
Heat On	closed		
Fault	closed		
24V dc		ground referenced	24V±2% @1A
Aux Port		not supported at this time	
Serial Port		RS485	

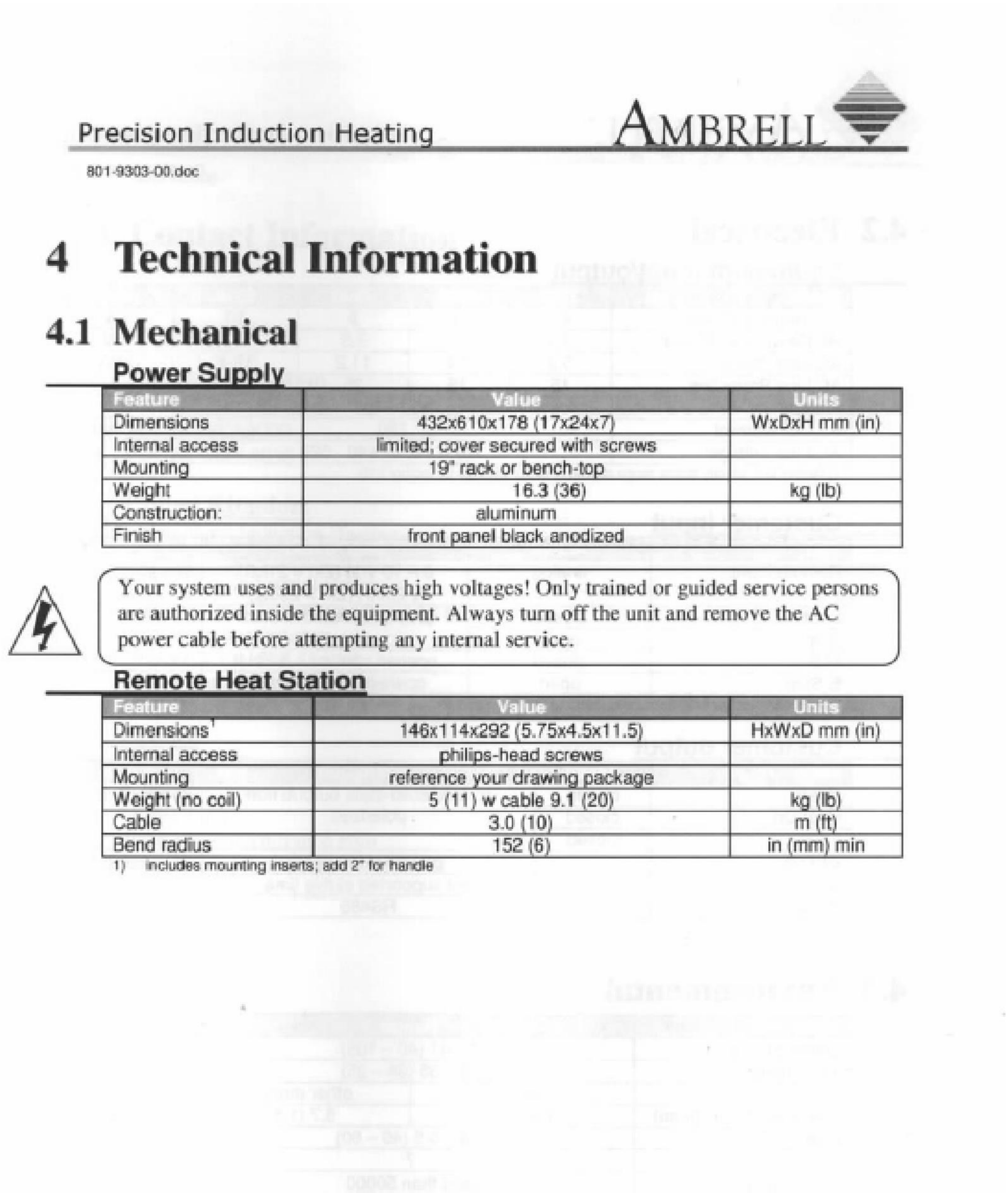
4.3 Environmental

Value	Range		Units
ambient temp	4 – 41 (40 – 105)		°C (°F)
water temp[1]	20 – 35 (68 – 95)		
	3542	other models	
flow (system minimum)	3.8 (1.0)	5.7 (1.5)	l/m (g/m)
pressure[2]	2.8 – 5.5 (40 – 80)		bar (lb/in^2)
pH	7		pH
conductivity resistivity @25°C	less than 50000 greater than 2000		µS Ω•cm
solids	less than 150		ppm

1.) Water temperature must not fall below the dew point in any case; condensation may result in nuisance problems or damage to the equipment

2.) You must ensure that the differential (inlet minus outlet) pressure falls within this range.

Induction Heater



Precision Induction Heating AMBRELL

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4 Technical Information

4.1 Mechanical

Power Supply

Feature	Value	Units
Dimensions	432x610x178 (17x24x7)	WxDxH mm (in)
Internal access	limited; cover secured with screws	
Mounting	19" rack or bench-top	
Weight	16.3 (36)	kg (lb)
Construction:	aluminum	
Finish	front panel black anodized	

Your system uses and produces high voltages! Only trained or guided service persons are authorized inside the equipment. Always turn off the unit and remove the AC power cable before attempting any internal service.

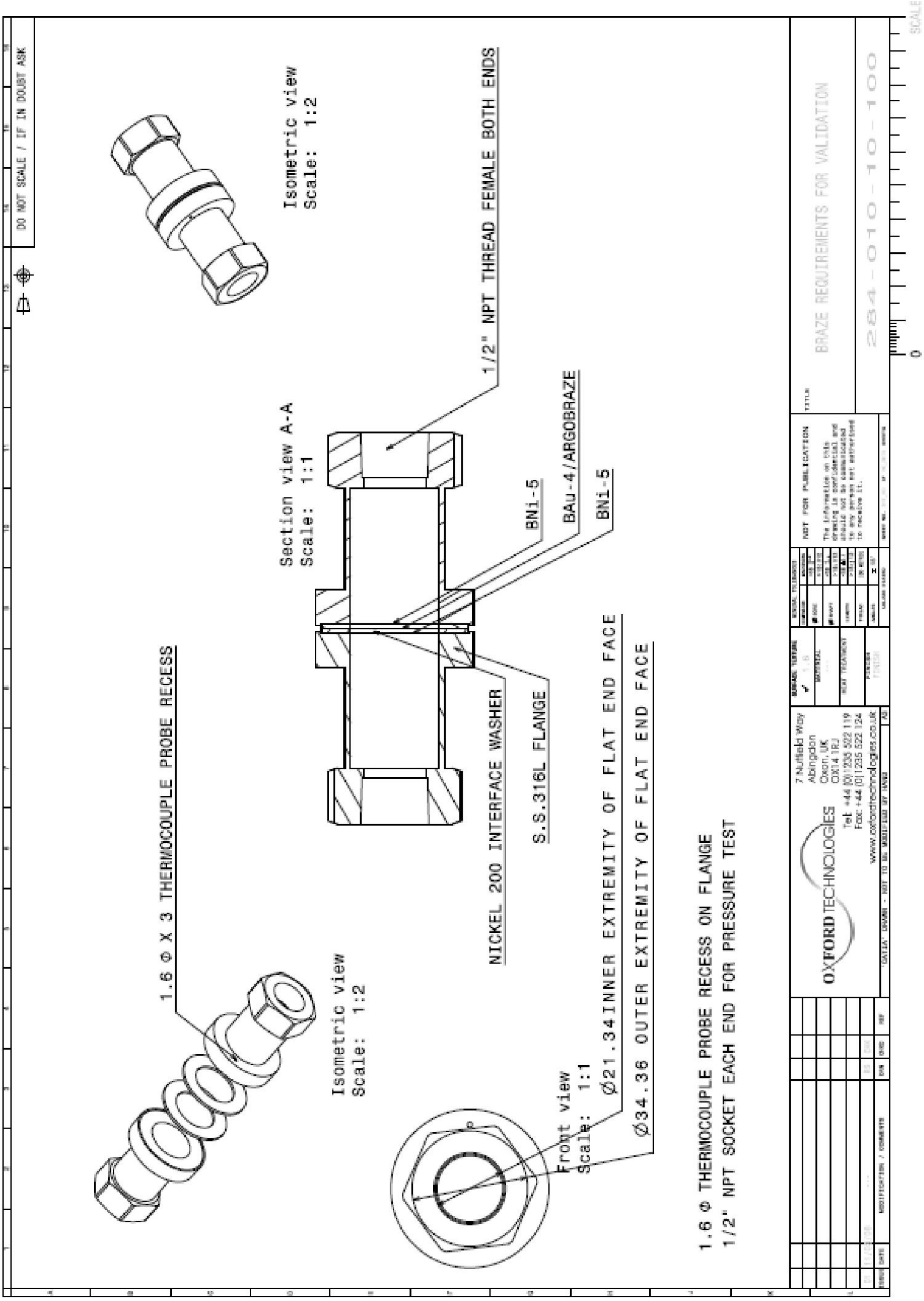
Remote Heat Station

Feature	Value	Units
Dimensions[1]	146x114x292 (5.75x4.5x11.5)	HxWxD mm (in)
Internal access	philips-head screws	
Mounting	reference your drawing package	
Weight (no coil)	5 (11) w cable 9.1 (20)	kg (lb)
Cable	3.0 (10)	m (ft)
Bend radius	152 (6)	in (mm) min

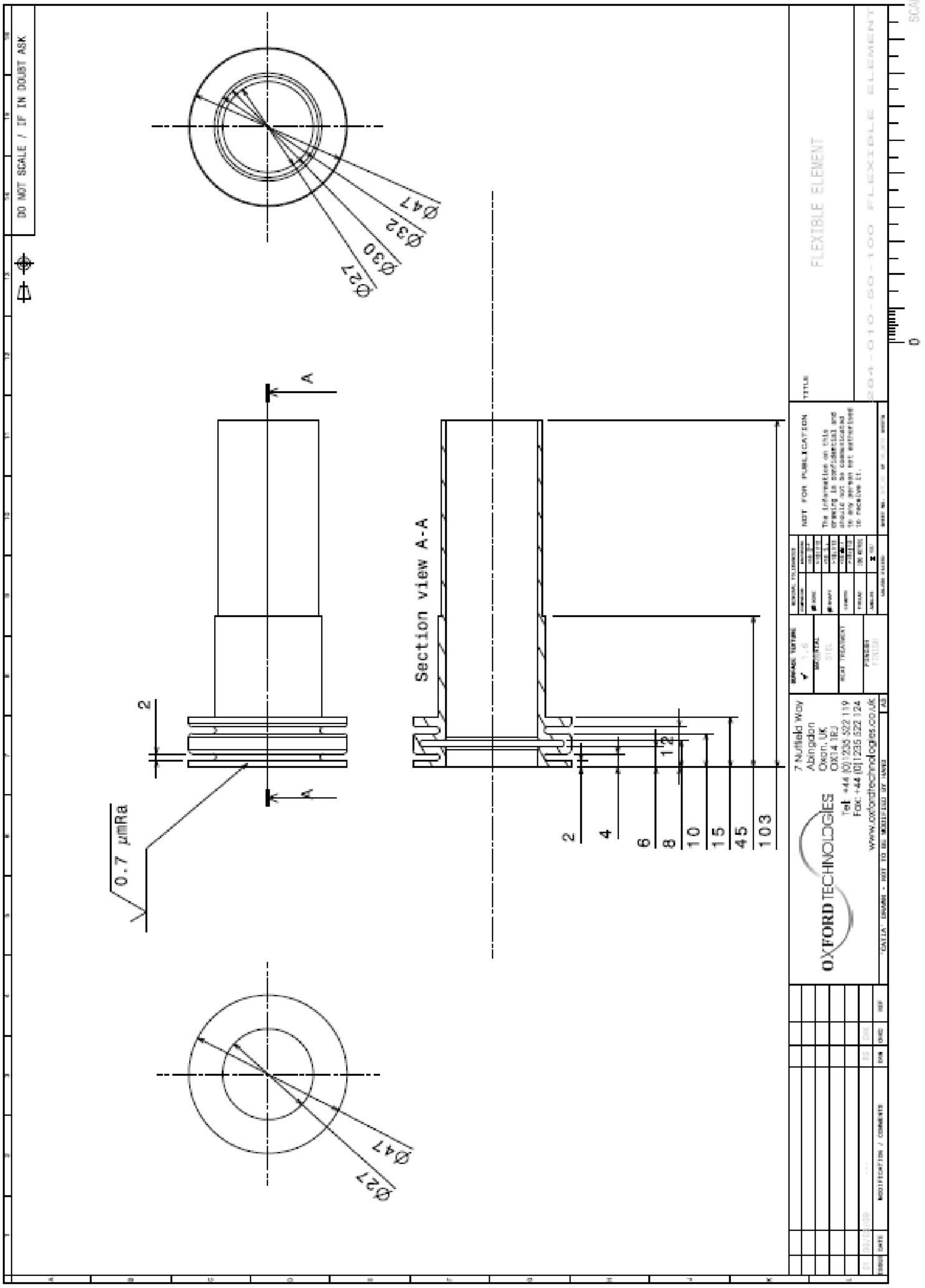
1) includes mounting inserts; add 2" for handle

APPENDIX B – Test Piece Drawings

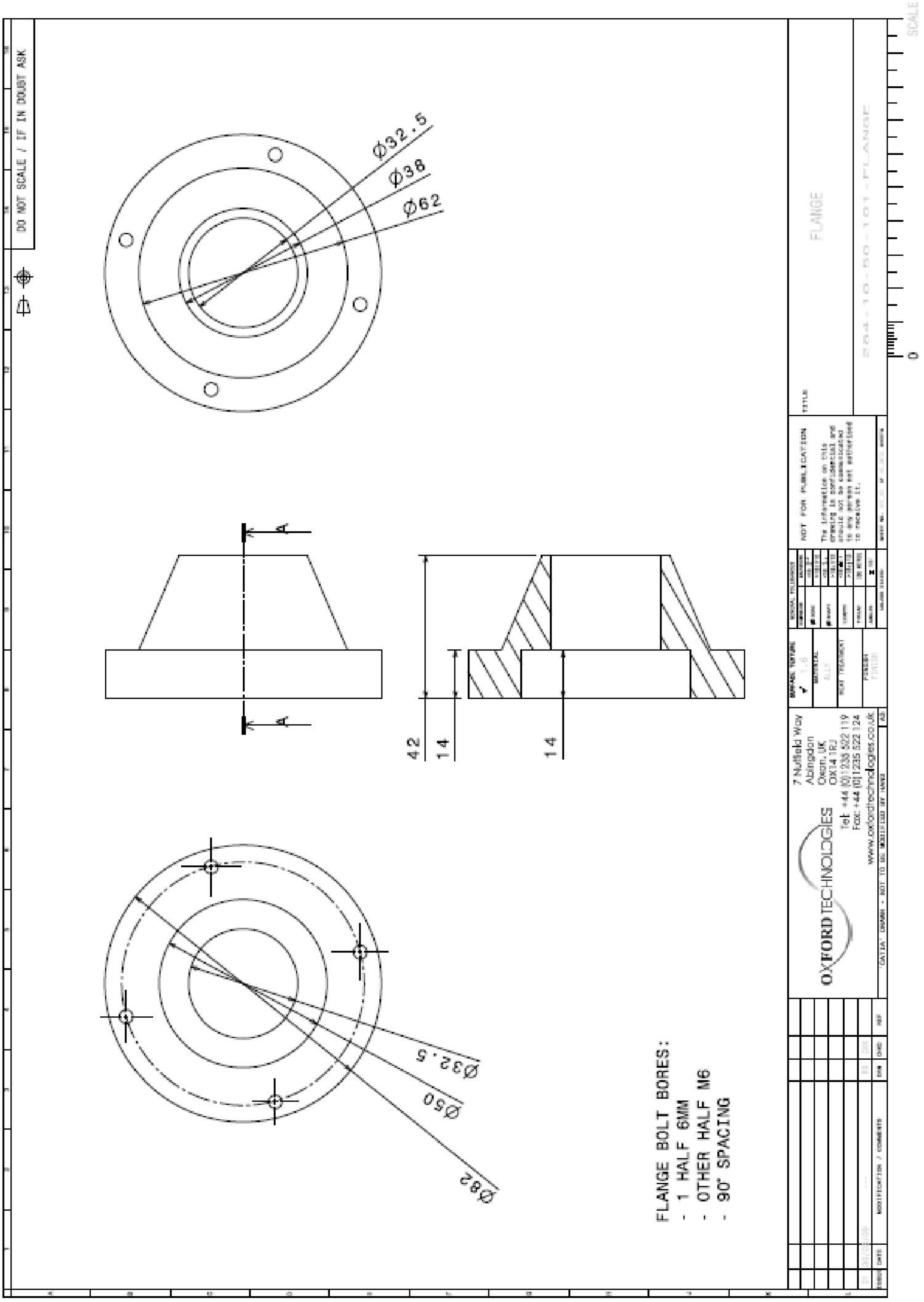
Pilot Study test parts



Full Braze Trial – Reinforced Flange



Full Braze Trial – Reinforced Flange



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