The University Of Sheffield.

NUCLEAR AMRC
ADVANCED MANUFACTURING RESEARCH CENTRE

INFORM

Intelligent Fixtures for Optimised and Radical Manufacturing

First phase R&D (2018–19)
supported by the Nuclear Innovation Programme

namrc.co.uk

Department for Business, Energy & Industrial Strategy

CATAPULT High Value Manufacturing

European Union European Regional Development Fund

The Inform project aims to develop a range of advanced techniques which could halve the cost and time of manufacturing large complex nuclear components.

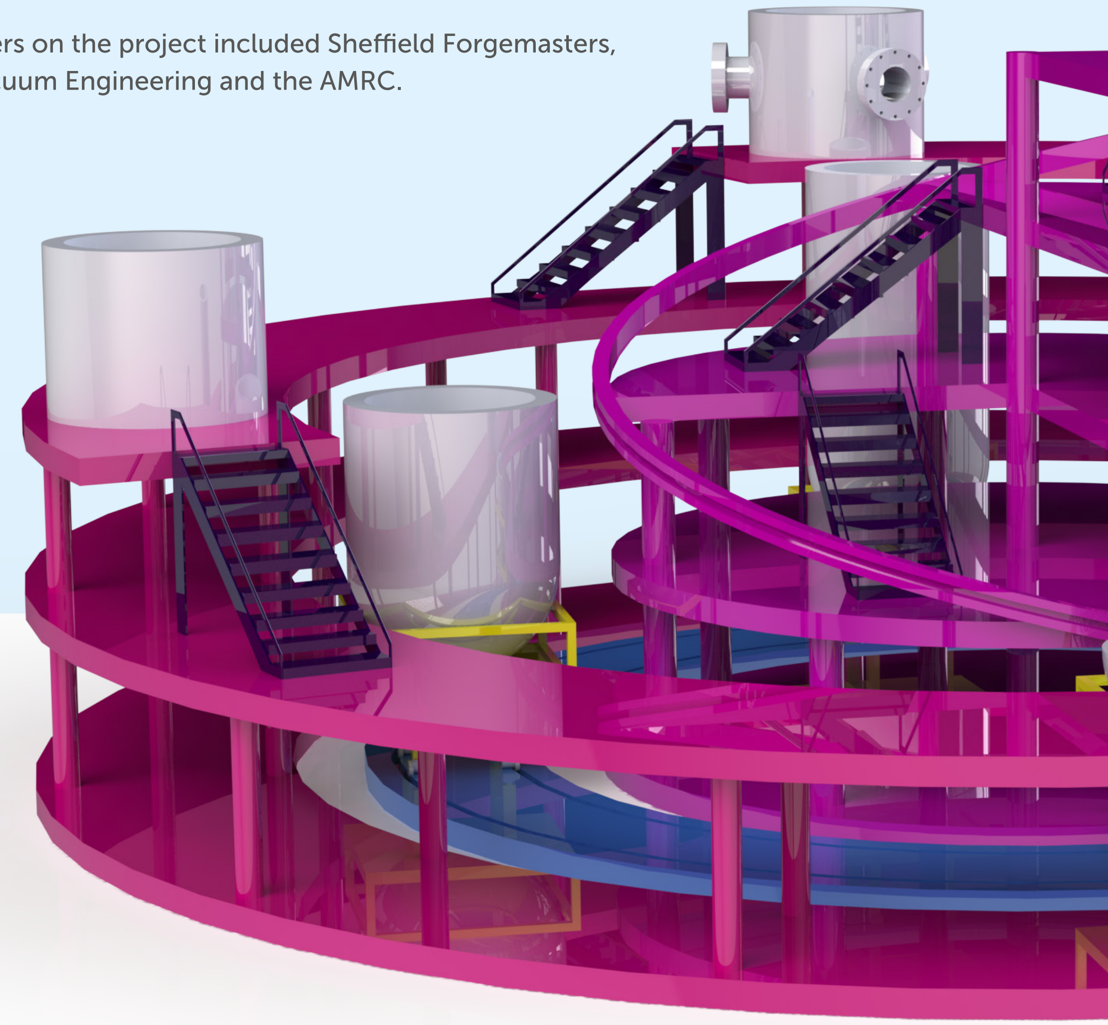
Inform (Intelligent Fixtures for Optimised and Radical Manufacture) focuses on technologies which can save time and money throughout the manufacturing process for large-scale nuclear components.

Technologies being developed through Inform include near-net forgings, optimised machining, local-vacuum electron beam welding, advanced fixturing and digital monitoring.

This report summarises the research to date, and sets out directions for continuing development.

The first phase of Inform was supported by £1.1 million project funding from the Department for Business, Energy & Industry Strategy (BEIS) as part of the Nuclear Innovation Programme.

Industrial and research partners on the project included Sheffield Forgemasters, MetLase, TWI, Cambridge Vacuum Engineering and the AMRC.



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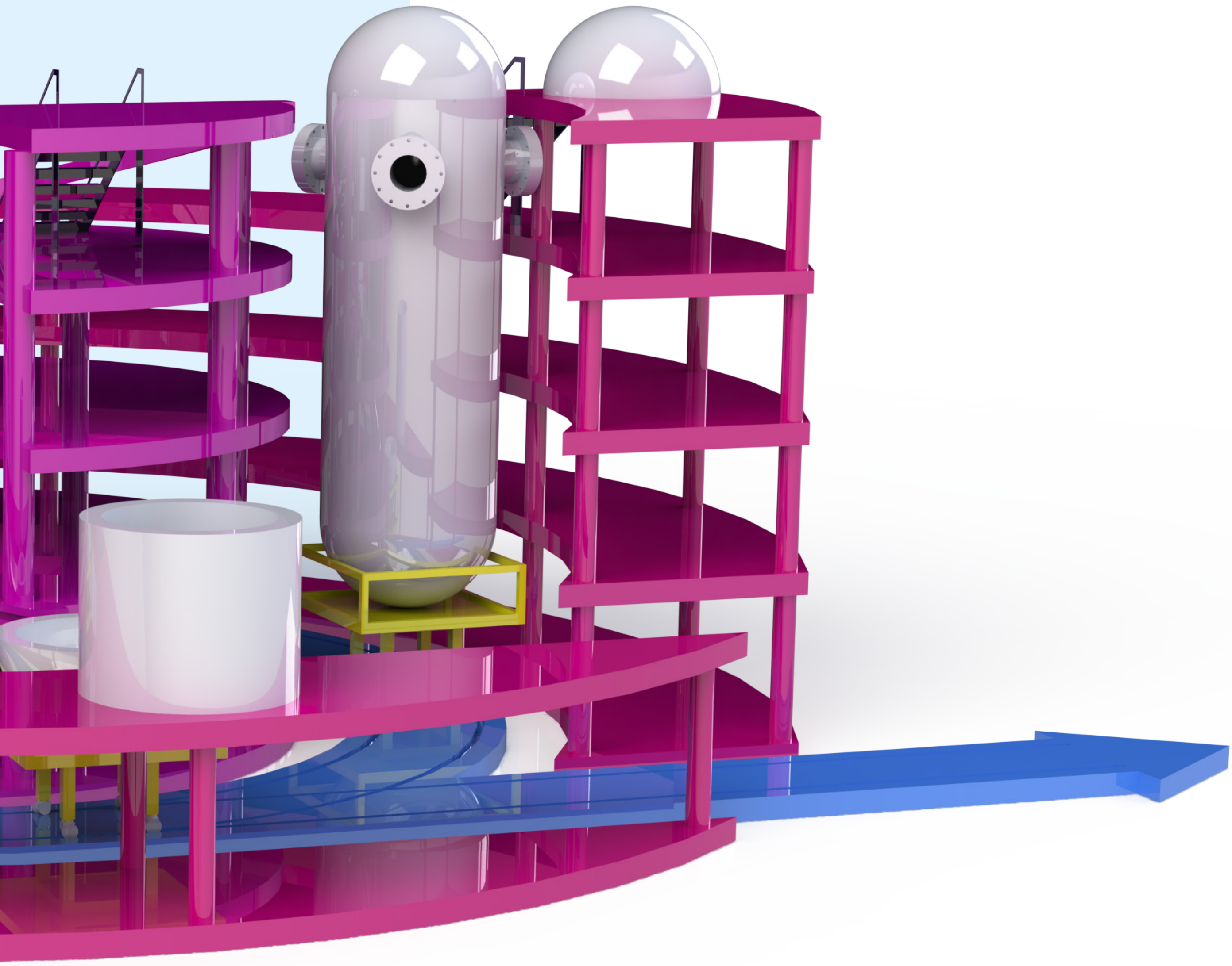


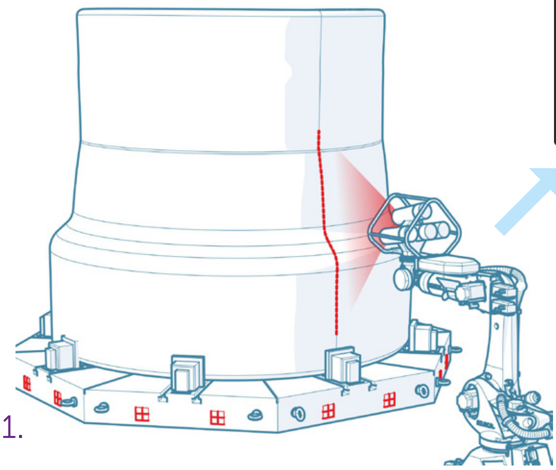
The Inform vision

The initial vision for Inform was to develop an intelligent adaptive fixturing system to ease the movement of large parts around a factory throughout the entire manufacturing cycle, and ensure precision through innovative forging, machining, welding, inspection and assembly processes.

The proposed technology would hold large components while they undergo the full range of manufacturing operations, and facilitate movement between platforms and machines. With sensors linked to actuators and manipulators, the fixture would automatically adjust its grip to minimise distortion during movement and manufacturing.

After initial studies identified the fundamental challenges to this long-term vision, the project broadened to consider a range of enabling technologies which could offer nearer-term benefits throughout the whole manufacturing process for large-scale nuclear components such as reactor pressure vessels.

Inform is supported by a range of nuclear industry partners – including reactor developers and operators, and decommissioning site owners – who ensure that the research is addressing industry challenges. The results will be shared with UK industry, including the Fit For Nuclear network of companies from along the supply chain.



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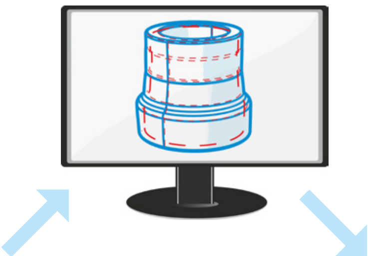

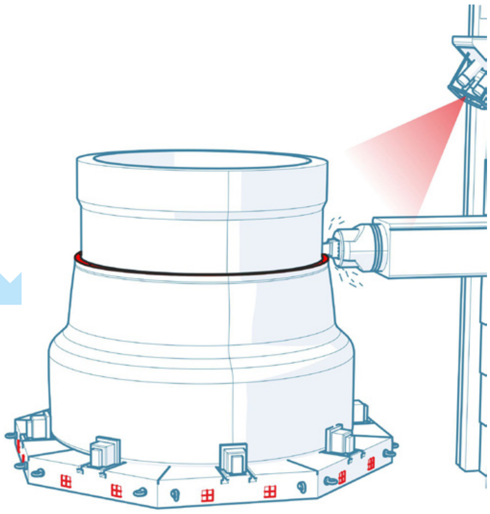

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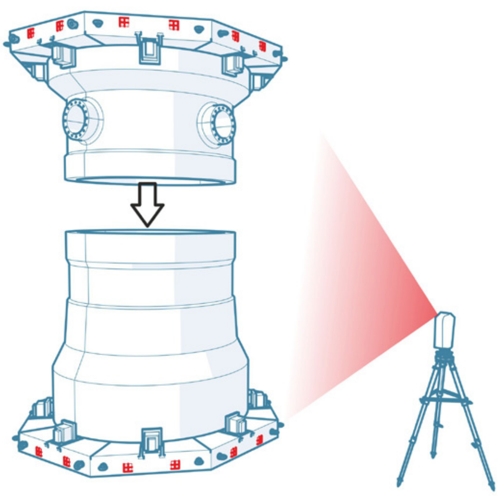

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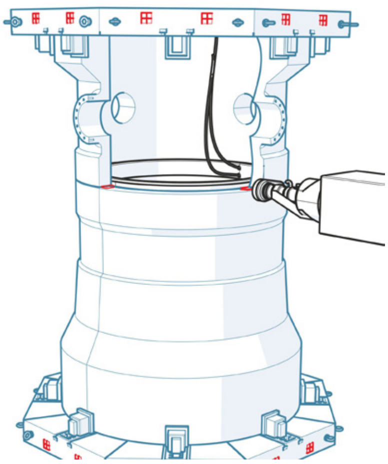

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First phase

Inform's first phase focused on developing and demonstrating the viability, at a small scale, of a range of technologies which underpin the Inform vision. These technologies were identified during an initial down-selection stage in 2017.

The 20-month first phase of Inform started in January 2018, and completed on schedule in August 2019.

Project partner Sheffield Forgemasters led research into optimising the forging process for pressure vessel sections, from steel-making to machined condition of supply.

The Nuclear AMRC investigated a variety of optimised machining and metrology techniques which could be applied to these forged sections, including near-net shape machining, advanced roughing algorithms, and supercritical carbon dioxide coolant to improve machining performance and increase tool life.

Welding research centre TWI worked with Cambridge Vacuum Engineering to develop local vacuum electron beam welding technology, to join very thick vessel sections in a single pass without needing a vacuum chamber large enough to contain the entire assembly.

MetLase, a joint venture between Rolls-Royce and Unipart, developed a proof-of-concept intelligent fixturing demonstrator for assembling a pressure vessel using this local vacuum electron beam welding technology.

And digital manufacturing experts from the University of Sheffield AMRC demonstrated how integrated sensors can provide continuous process monitoring through the manufacturing process, improving efficiency, quality and safety.

Ultimately, the integrated technologies developed by Inform could cut cost and time for manufacturing large complex nuclear fabrications on a series of dedicated platforms by at least 50 per cent.

Inform's first phase focused on developing and demonstrating the viability of a range of technologies which underpin the Inform vision

Local vacuum electron beam welding

Lead partner: TWI

TWI and partners developed a demonstration system for electron beam welding without the need for a large vacuum chamber.

Electron beam welding can join very thick vessel sections in a single pass but, because the electron beam requires a vacuum to be effective, standard techniques need a vacuum chamber big enough to fit the entire assembly.

If you can create a local vacuum around the welding area, you can avoid that size limit, reducing capital and operational costs, and allowing electron beam welding to be used in new applications.

TWI worked with vacuum specialists Cambridge Vacuum Engineering (CVE) to develop a local vacuum electron beam end effector, designed to meet the requirements of a pressure vessel shell. TWI has previously worked on similar systems, but the Inform technology includes a number of innovations to improve productivity and cost efficiency.

Advanced features include a low-cost interchangeable seal carrier to allow the end effector to weld vessels of varying diameters, and a second sliding seal to maintain vacuum while the local vacuum head moves between positions. The head also includes a cooled fronting bar to prevent loss of molten metal and to form a weld cap

The local vacuum end effector.

profile on the outside of the vessel, plus a vacuum link to the internal root side to stop the weld metal being displaced by the pressure differential.

The system features an integrated beam conditioning and quality assurance station, which reduces the risk of arcing by conditioning the welding gun over a cooled heat sink before welding. It also allows a probe to be introduced to measure the beam power and profile.

The prototype system was assembled and subjected to static and dynamic vacuum tests at TWI's technology centre in Middlesbrough, then taken to Cambridge for commissioning on CVE's EBFlow welding machine.

In initial trials, the system successfully demonstrated full penetration melt-runs of one metre's length in an 80mm-thick steel mock-up of a pressure vessel shell.

Further work is required to achieve a full weld between sections, and to optimise the process.

Maintaining the integrity of the seal is a major challenge – during the trials, the seal was replaced after each use to avoid the risk of failure. Further development of the seal design is needed to reduce the risk of damage while minimising the risk of leakage, and to allow easy replacement when needed.

With further development, local vacuum ebeam welding could reduce process time by more than 90 per cent compared with arc welding for thick sections of nuclear-grade steel. The process will require extensive work to develop a code case before it can be used in nuclear applications, but could also be exploited in other industries such as aerospace and defence.

Welding trials on CVE's EBFlow machine.

Optimised machining

Lead partner: **Nuclear AMRC**

Rough machining from scan data

To improve the rough machining of large components from forged stock, we developed an innovative method to use optical scan data to generate machine tool paths in a fraction of the time of current methods.

Large nuclear components such as pressure vessel sections typically start life as forged billets. Although close to the desired shape, these forgings have a rough surface with irregular lumps and bumps which need to be removed before the fine machining of features can begin.

Conservative cutting strategies are typically used for this rough machining. These reduce the risk of damaging the workpiece or tool, but are inefficient as the tool spends a significant amount of time not connecting with the workpiece – in machinists' language, "cutting air".

The roughing process can be improved by creating an accurate model of the raw workpiece and optimising the cutting strategy. However, the computer-aided manufacturing (CAM) software which drives numerically-controlled machine tools typically can't handle the data output from optical scanners. Scan data takes the form of a 3D point cloud, which can be converted to a polygon mesh model using well-established techniques.

Current practice is to use scan data or manual measurements to reverse-engineer a model using computer-aided design (CAD) software, then use this to create CAM data. This can take up to a week for complex workpieces.

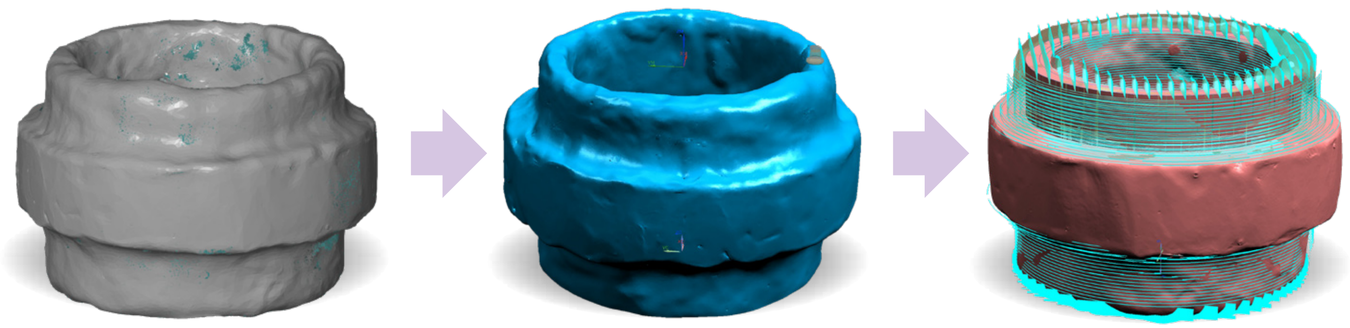
We developed a novel scan-to-CAM approach which avoids this intermediate CAD stage by generating toolpaths directly from mesh data. By matching the mesh model with a CAD model of the finished component, we can ensure that material can be removed as evenly and efficiently as possible around the workpiece.

To prove the viability of this approach, we created a scale model of a raw forging for a generic pressure vessel component, with a range of common features, and scanned this at full resolution.

As well as avoiding time-consuming CAD modelling, this scan-to-CAM technique demonstrated significant efficiency improvements over standard practice. In early trials, we reduced cutting time by 40 per cent using a commonly-used CAD/CAM software package.

We also investigated software techniques to optimise the alignment of the forged workpiece, reducing set-up time and further improving efficiency.

With development, this scan-to-CAM technique could improve machining efficiency and reduce tolerances for near-net shape manufacture by forging, casting, additive manufacturing, or hot isostatic pressing of metal powder.



Scan Mesh CAM

Supercritical coolants

Replacing traditional oil-based coolants with supercritical carbon dioxide can significantly increase tool life when machining nuclear-grade steel, and further improve productivity by reducing the need for post-process cleaning.

A supercritical fluid combines the physical properties of a liquid and a gas, which means it has the density to remove swarf while retaining most of the desirable flow properties of a gas.

Earlier research has shown that, for many metals, the best effects come from combining supercritical CO_2 with the minimum quantity lubricant (MQL) technique – using as little as one millilitre per minute of a mineral or vegetable oil, dissolved in the supercritical fluid.

This avoids the health risks and costs associated with using large quantities of oil-based coolant, and allows the use of in-machine sensing and monitoring tools.

We carried out extensive milling trials using supercritical CO_2 and MQL to investigate its effects on the machinability of SA508 steel for nuclear components, using our large Starrag HEC1800 machining platform.

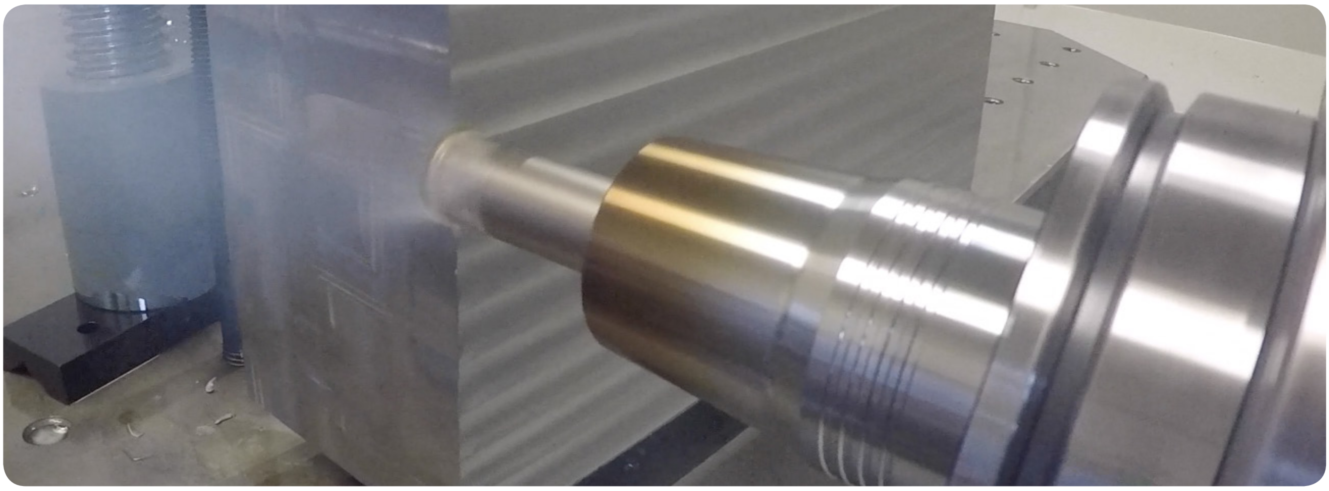
The trials consistently demonstrated increases of up to 220 per cent in tool life compared with the conventional cooling method.

Our studies considered the effects on tool life, tool wear mechanisms, cutting forces and surface integrity under a variety of cutting conditions. Tool wear mechanisms differed depending on the coolant type being used, but we found no detriment to the material surface condition.

Supercritical CO_2 provides additional benefits in machining large components for quality-critical applications. Even with MQL, the components require little or no cleaning to remove contamination and residues after machining.

It also reduces health and safety risks associated with large quantities of oil-based coolant, which can form a mist which is harmful if inhaled. Further work is required to fully quantify the benefits.

Further research is also needed to optimise cutting conditions to maximise the productivity benefits for a range of nuclear sector applications.



Machining trials using supercritical carbon dioxide coolant.

Intelligent fixturing

Lead partner: **MetLase**

Fixturing specialist MetLase designed an innovative assembly process for welded reactor pressure vessels which could significantly reduce cost and lead time for a new generation of small modular reactor (SMR).

Fixturing systems for large nuclear pressure vessel assemblies need to withstand substantial loads, and are typically constructed from welded civil engineering beam structures.

MetLase's proprietary fixturing system removes the need for welding when creating the fixture. It uses laser-cut fixturing with integrated fasteners for the precise location of high-load components. It is quicker to manufacture and replicate, uses less metal, and avoids the risk of weld distortion to the fixture which would require corrective machining.

The system was originally designed for aerospace, but MetLase has now developed the system for larger and heavier assemblies. Being part of the Inform consortium allowed the company to test the full capability of its system for the heaviest engineering applications.

The project presented a series of challenges. The first was to generate optimised location and alignment methods for large cylindrical components, while allowing sections to be joined by a local vacuum electron beam welding system.

Initial concept generation showed that the silo-build concept, in which the vessel is vertically lowered as each section is added, would allow the highest level of tolerance control throughout assembly. The sunken silo also provides shielding for heat treatment of the welds.

Building the vessel vertically also optimises the process forces. The location mandrel acts like a machine tool's chuck, lifting and lowering the component into place, while ensuring the correct location and alignment of each cylindrical section. The join between components can then be presented to the electron beam welding head.

The MetLase team carried out an initial assessment of their fixturing system's applicability to SMR pressure vessels, using finite element analysis (FEA) techniques to assess the effects of the high loads.

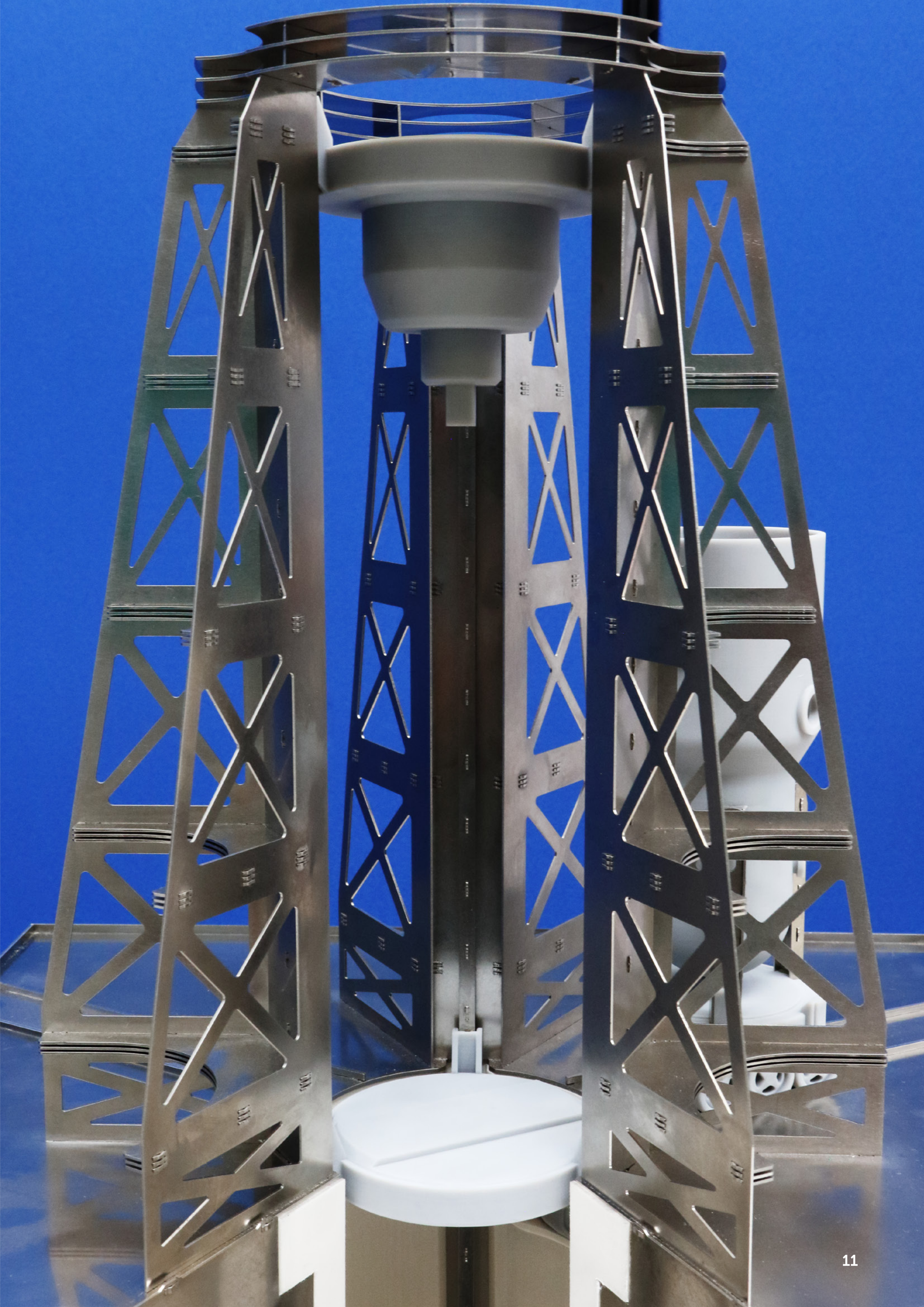
The team modelled the loads caused by a 20 tonne pressure vessel and the weight of the tooling itself, in various configurations of plates and beams. Having identified the core constructional elements of the fixturing system, the team used FEA to predict structural load behaviours and optimise fixture design. These core element morphology studies generated a wealth of information which can be used to develop fixturing for future heavy engineering applications.

The team also used FEA to study the stresses on the joints between fixturing sections, using innovative methods to efficiently model complex fixturing assemblies with multiple joints. The researchers developed a new simplified approach to modelling these joints, with promising initial results.

To showcase the Inform concept and demonstrate the potential of its fixturing technology, MetLase produced a 1:30 scale model constructed from laser-cut jointing features and 3D-printed components, representing an innovative solution for SMR pressure vessel production.

The team continue to refine the FEA methods developed through Inform. Further research could tackle physical testing of large structures to validate the FEA models, and investigate a wider range of large fixturing structures and joining approaches for heavy engineering applications.

Right: Desktop demonstrator of the Inform fixturing concept.



Forging

Lead partner: **Sheffield Forgemasters**

Innovative technologies for forging could radically improve efficiency in producing pressure vessels and other key components for a new generation of reactor design.

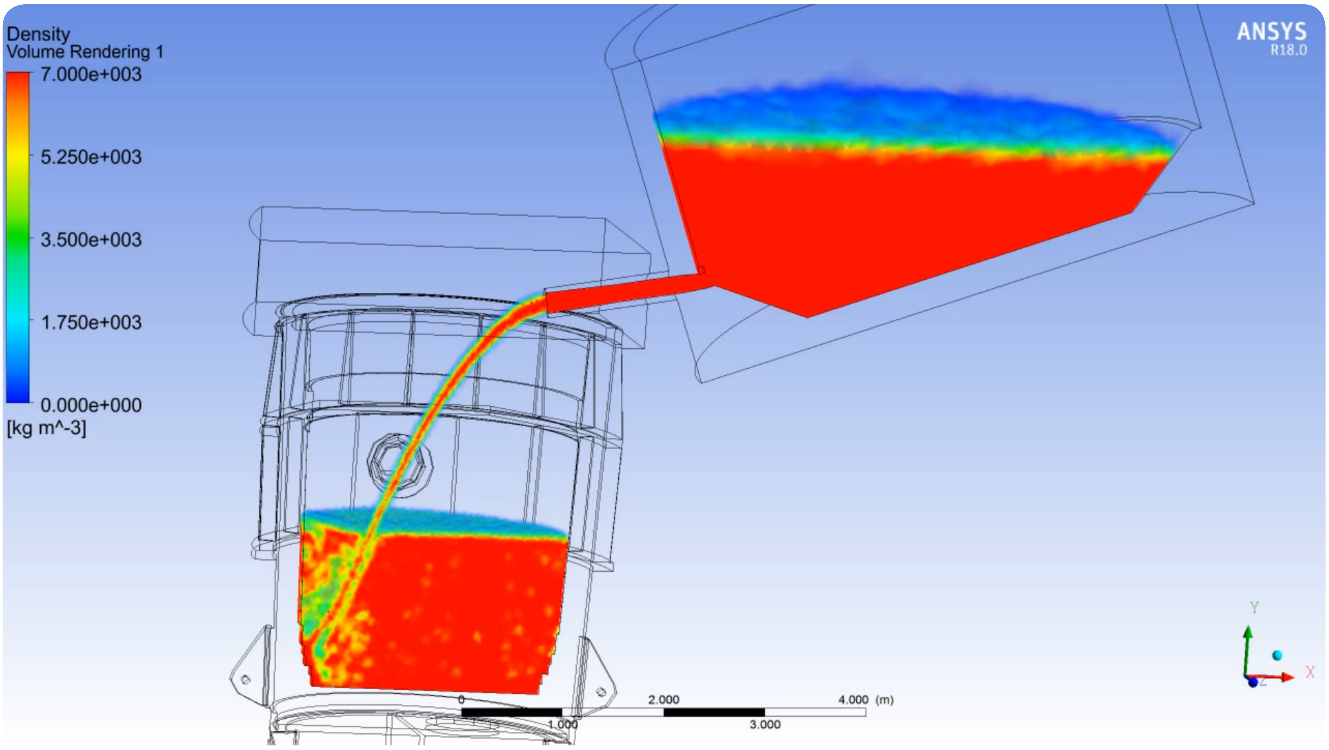
Sheffield Forgemasters RD26, the research wing of the UK's largest forging group, studied emerging technologies and best practice from other sectors which could be exploited in large-scale open die forging of nuclear grade alloys.

The team reviewed the small modular reactor (SMR) and advanced modular reactor (AMR) designs being considered for development in the UK. These include lead-cooled or sodium-cooled fast reactors, molten salt reactors, and very high temperature light-water reactors, as well as potential designs of commercial fusion reactors.

In each case, the Forgemasters team identified the most appropriate alloys for their reactor pressure vessel shells and other key forged components, and considered potential manufacturing challenges in forging, metrology, heat treatment and machining.

Ring rolling, sheet forming and rotary forging were identified as key capabilities for the efficient production of thin-walled vessels for advanced low-temperature reactors.

The team investigated robust modular forging tools which can reduce the overall cost of forging and forming, and increase production flexibility and efficiency by allowing rapid changeover between processes. Modular tooling can allow components to be forged closer to their final shape in mid to high-volume manufacture.



The team investigated opportunities for process improvement in vacuum stream degassing.

Forgemasters also considered how the steel is processed before forging, as this can have a significant impact on performance. One area for improvement is in vacuum stream degassing, which removes hydrogen and other impurities from the steel by pouring the molten metal from a ladle into a vacuum vessel. The team investigated laser scanning of the vessel seals to monitor their condition and optimise process efficiency, and considered new vacuum pumping systems which can reduce costs and improve process control.

Further development of the hollow ingot casting technology could also improve production efficiency, reduce time and lower costs in the forging process for reactor pressure vessels and other large cylindrical components. Sheffield Forgemasters pioneered the hollow ingot technique in the 1950s, and has recently developed advanced techniques to improve material properties and extend service life. New design approaches will be needed to produce hollow ingots for the smaller pressure vessels of some new reactor designs.

Finally, the team identified a number of real-time metrology techniques to monitor the dimensional accuracy of forged components while they are still on the press. Currently, this is done manually using mechanical gauges. Techniques such as laser projection and laser scanning can improve accuracy and provide near-instant measurement to ensure conformance, while reducing safety risks to workers.

Extensive work will be required to bring these techniques into commercial production, but the Forgemasters study has identified the way forward for a host of advances in forging technology for advanced reactors.

Hollow ingots allow more efficient forging of large nuclear components.

Digital technology

Lead partner: **University of Sheffield AMRC**

The University of Sheffield Advanced Manufacturing Research Centre (AMRC) developed a technology demonstrator of intelligent fixturing sensors to provide continuous process monitoring in nuclear manufacturing.

The technology aligns with the so-called fourth industrial revolution (4IR, or Industry 4.0) by combining digital and physical systems to improve productivity and allow autonomous decision-making.

Starting from a requirement for continuous monitoring and reporting on the status of the fixture and its located component, the AMRC team developed concepts for a fixturing system to allow location tracking, movement monitoring, and automatic alignment.

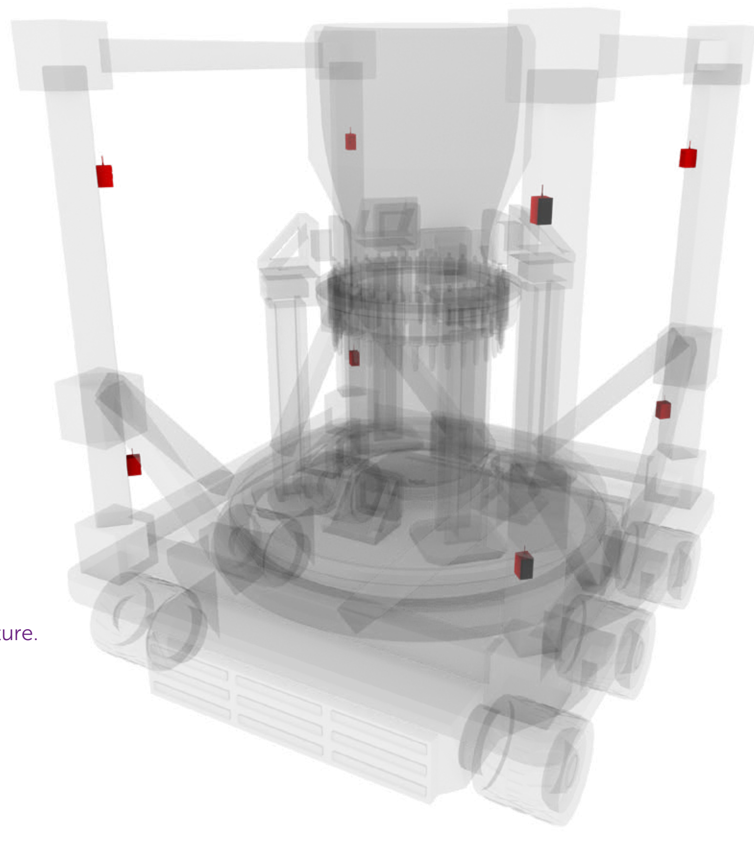
The demonstrator used the LoRaWAN (long range wide area network) wireless platform, with a variety of low-power sensors mounted on a fixture. This platform is used in other applications such as building automation and logistics, but has not yet been adopted in the nuclear sector. The system can be integrated with a novel fixture which incorporates a range of Inform technologies, or retro-fitted to existing fixtures.

A selection of sensors including non-contact thermometers, accelerometers and GPS-based position trackers were applied to a physical scale model of a fixture, featuring a rotating platform with 3D-printed model of a vessel component. The sensors wirelessly feed data to a laptop which records and displays information through a customised dashboard.

As well as enabling monitoring, location tracking and analytics of the fixture and component throughout the manufacturing process, the system can also reduce set-up time in repeat production, and allow predictive maintenance.

The demonstrator shows that applying 4IR technologies to fixturing for large-scale nuclear manufacturing can improve efficiency and ultimately reduce the cost of manufacturing. The system can also reduce safety risks by identifying potential problems and preventing accidents.

Further work is required to fully understand the fixture process life cycle, and develop and test the hardware for industrial environments.



Concept design showing sensors mounted on the Inform fixture.

Metrology

Lead partner: **Nuclear AMRC**

With many of the Inform innovations relying on accurate measurement, the Nuclear AMRC metrology team identified a range of technologies to meet the project's specific requirements in forging, machining, assembly and welding.

Forging requires high rates of data capture, a large measurement volume, automation and non-contact measurements. We found a laser scanner referenced by an optical or laser tracker to be the most appropriate technology. If the measurement volume is less than 4.5 metres and automation is not necessary, laser scanning with a measurement arm is also suitable.

For advanced machining operations, we recommend a laser scanner referenced by a laser tracker, alongside on-machine probing. The laser scanner can digitise the part surface to allow the part set-up and toolpath to be optimised, and allow non-contact measurement across large volumes.

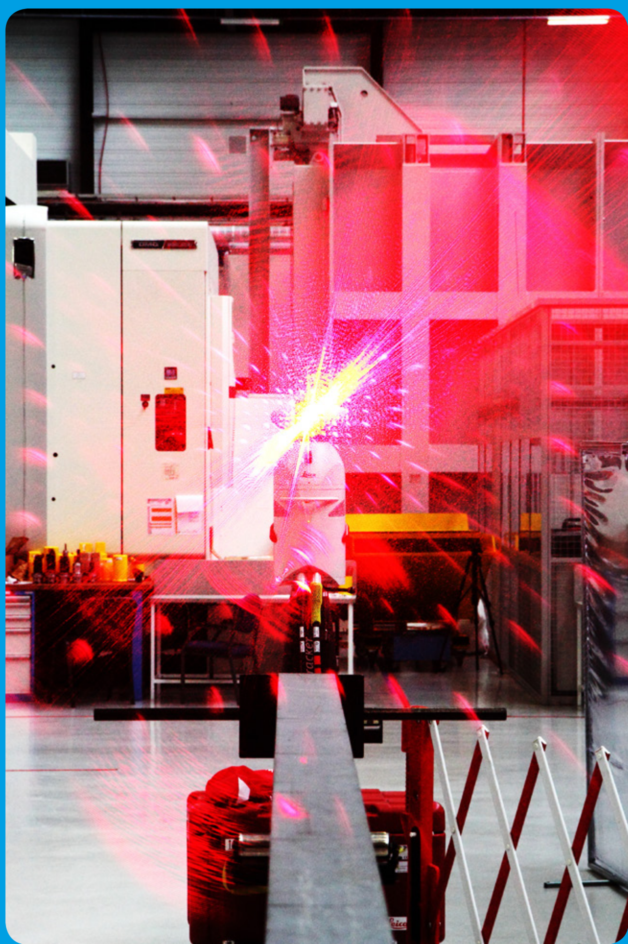
On-machine probing can meanwhile provide in-process verification, supported by additional measurements from the laser tracker to verify machining axes.

For assembly operations, laser trackers remain the most appropriate technology. These represent a significant capital investment if multiple trackers are required, though further development could reduce this barrier to adoption.

An alternative approach is to use photogrammetry, although this currently has less capability for automation. Emerging techniques such as divergent beam frequency scanning interferometry are promising but need considerable development.

Welding operations considered in Inform will require a robust system which can survive the welding environment, as well as non-contact inspection over a large measurement volume. This can be achieved by laser scanning with a tracker, or with a measurement arm for smaller components.

Electron beam welding requires highly accurate pre-weld inspection, so a laser scanning technique would need careful validation to ensure it meets requirements. If reference markers can be placed on the part, photogrammetry may also be used.



Laser scanning allows non-contact measurement over large volumes.

Dissemination & business engagement

Results from the Inform programme were shared with the UK's nuclear manufacturing supply chain throughout the project.

Showcase events

The Nuclear AMRC organised two industry-focused events to showcase Inform and other projects funded by the Nuclear Innovation Programme (NIP).

By organising events covering a range of NIP projects, we were able to maximise our audience, and highlight complementary research and collaboration opportunities.

In January 2019, we hosted a special meeting of the Nnuman community, an industry-led forum to support the development of the next generation of nuclear technology. The community was established in 2018 as a continuation of the technical advisory board for the EPSRC-funded Nnuman (New Nuclear Manufacturing) programme.

The Nnuman seminar at the AMRC Knowledge Transfer Centre discussed projects from across the advanced manufacturing and materials strand of NIP, and was attended by over 75 members of the nuclear R&D community.

We also organised the Nuclear Innovation UK conference in July 2019, a major industry conference presenting research from all strands of NIP. The two-day conference in Sheffield brought together around 275 delegates from industry and academia, and included technical presentations on Inform from the Nuclear AMRC's Ben Cook, plus an opportunity to visit our workshop to see the technology demonstrators.

The Inform technologies have also been presented to many other industrial and academic visitors to the Nuclear AMRC – our research factory in Rotherham welcomes around 10,000 visitors a year.

Conferences

Researchers from the Nuclear AMRC and partners presented their work at industrial and academic conferences worldwide, including:

- International Congress on Welding, Additive Manufacturing and Associated Non-destructive Testing (Metz, France).
- 72nd International Institute of Welding Annual Assembly (Bratislava, Slovakia).
- ASME Pressure Vessels and Piping Conference 2019 (Texas, US).
- Nuclear Innovation Programme suppliers day (Birmingham, UK).

We also held regular consortium meetings with all partners and stakeholders – including BEIS and the Nuclear Innovation Research Office – to share the latest developments and ensure consistent delivery of the Inform programme.

Delegates at the Nuclear Innovation UK conference view Inform technologies during a visit to the Nuclear AMRC workshop.


Look into the future of
nuclear innovation

Future factories, modular design and nano-structured steels were just a few of the manufacturing and materials technologies discussed at a Nuclear AMRC seminar exploring research funded through the Nuclear Innovation Programme.

Publicity

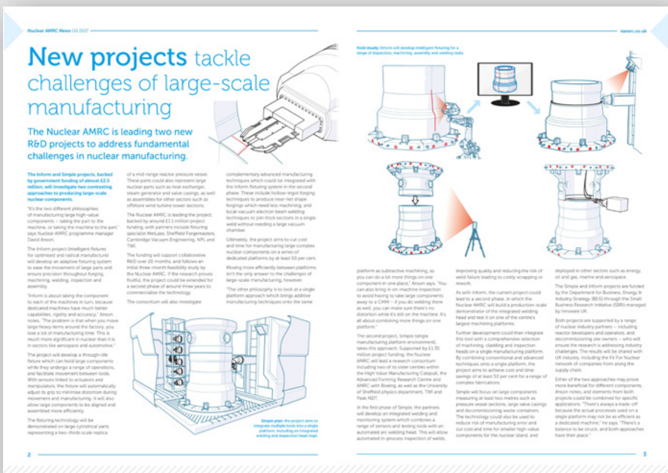
Alongside the dissemination events, we promoted and shared the Inform project with our wider supply chain audience through a variety of communication channels including the quarterly *Nuclear AMRC News*, online and social media.

A dedicated page on the Nuclear AMRC website featured regular updates:
namrc.co.uk/services/crd/inform

Articles were placed in key industry titles including *The Manufacturer* and *Nuclear Engineering International*. And, in a joint entry with the Simple project, the Inform team were finalists in *The Engineer* magazine's Collaborate to Innovate Awards 2019.

Press announcements were also shared through our network of stakeholders, including the University of Sheffield and High Value Manufacturing Catapult, to maximise our reach.

Researchers from all partners continue to publish papers based on their Inform work through a variety of academic publications.


New projects tackle challenges of large-scale manufacturing

The Nuclear AMRC is leading two new R&D projects to address fundamental challenges in nuclear manufacturing.

Partners

The **Nuclear Advanced Manufacturing Research Centre** helps UK manufacturers win work in the nuclear sector. We work with companies of all sizes to develop new technical capabilities, raise quality and reduce risk.

The Nuclear AMRC is backed by industry leaders and government, and is part of the University of Sheffield and the High Value Manufacturing Catapult.

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Sheffield Forgemasters is the world's largest independently owned forgemaster, and the only UK firm to hold ASME NCA3800 certification for civil nuclear castings and forgings. Its RD26 business supports research into the manufacture of carbon, low alloy and stainless steel grades for heavy forging and casting applications.

www.sheffieldforgemasters.com

MetLase is a mechanical engineering consultancy joint venture between Rolls-Royce and Unipart. Using precise laser cutting and press-brake material forming, MetLase can swiftly design and produce tooling, fixturing and components which are up to 10 times more accurate than using additive layer manufacturing, and typically one third of the cost.

www.metlase.com

TWI is one of the foremost independent research and technology organisations, spanning innovation, knowledge transfer and problem resolution across all aspects of welding, joining, surface engineering, inspection and whole-life integrity management.

www.twi-global.com

Cambridge Vacuum Engineering designs and builds process solutions, and has more than 60 years of experience manufacturing electron beam systems and vacuum furnaces.

www.camvaceng.com

The **University of Sheffield Advanced Manufacturing Research Centre** develops advanced machining, materials and digital technologies of practical use to industry. It is part of the High Value Manufacturing Catapult.

www.amrc.co.uk

Next steps

In the first phase of Inform, we investigated a variety of innovative and emerging forging, machining, welding, inspection and assembly processes which can radically reduce the cost and time of manufacturing large nuclear components.

For some of these processes, our consortium explored a range of potentially beneficial technologies, and identified priorities and routes for future research.

For others, we moved specific technologies closer to commercial exploitation for the nuclear sector. Ongoing development can put these into production in the medium term, improving productivity and capability in the UK supply chain.

In the longer term, all these technologies can be brought together in an integrated platform for large-scale nuclear components which will ensure precision and efficiency through the whole manufacturing process.

This could be a critical enabling technology for the cost-effective production of pressure vessels and other key components for a new generation of small and advanced modular reactor.

Ultimately, the integrated technologies developed by Inform could cut cost and time for manufacturing large complex nuclear fabrications on a series of dedicated platforms by at least 50 per cent. This will give UK manufacturers a sustainable competitive advantage, and reduce the cost and risk of future nuclear technologies.

Conceptual model of a pressure vessel assembly platform combining all the Inform technologies.

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CATAPULT
High Value Manufacturing

Working with
Innovate UK

Project partners

SHEFFIELD FORGEMASTERS

MetLase
A JOINT VENTURE BETWEEN ROLLS-ROYCE AND UNIPART

TWI

CVE
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