TBM Structural Material Fabrication and Status of TITAN Program Planning

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Compositions of RAF/M Steels for ITER TBM Structural Components

The U.S. led the development of T91 and the first generation of RAFM steels derived from it.

- Fusion materials programs in the U.S., EU, Japan, Russia and China have developed similar reduced activation ferritic-martensitic (RAFM) steels.
- All RAF/M steels are based on T91, a high-strength, creep resistant steel developed in the 1970s for fossil-fired steam plants.
- A code-qualified data base on production, fabrication of plates and tubes, mechanical properties and joining exists.
- T91 would be used for fabrication development.
- There is a need for a sufficiently large heat of F82H or Eurofer 97 for fabrication of all prototypes and final articles.

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<tr>
<th>Element</th>
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<th>9Cr-2WVTa</th>
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The technical approach was developed on the basis of data and information from four primary sources:

- Evaluation of the technical achievements of the EU program on the development of fabrication technologies for first-wall, grid plate and assembly for the HCCB and HCLL TBMs, including site visits to FZK, EFDA, and ENEA-Brasimone.
- Evaluation of the Japanese program on fabrication of FW components for the WCCB TBM.
- Meetings with U.S. commercial vendors to discuss application of the state-of-the art HIPing and investment casting technologies to U.S. TBM designs and discussions on the fabrication of square section tubing, and welding technologies.
- Experience within the U.S. Fusion Materials Program on mechanical property measurements, evaluation of joints, microstructural analysis and neutron irradiation testing.
EU Fabrication of Sub-Components: Screening and Optimization

- 2-steps HIP (FW, CP, SP, caps)
- 1-step high-pressure HIP with Cu inserts (FW, CP, SP, caps)
- Tube forming + HIP process (FW)
- HIP of rectangular tube process (FW only)

….and other under development

Investment Casting is an Attractive Alternative to HIP

- ~70 square tubes will need to be joined by HIP to form the first-wall. Consequently a large fraction of the first-wall structure consists of joints.
- Structural failures often originate in joints since these regions are typically the “weakest link”. Extensive NDE is needed to ensure structural integrity.
- Investment casting will be explored as an alternative to HIP to dramatically reduce amount of joined material. This should increase reliability and decrease the amount of NDE required.
- Investment casting is potentially less expensive than other fabrication methods.
- Complex castings of 9-10 Cr steels have been produced with mechanical properties similar to those of wrought products.
Temperature Dependence of $\sigma_y$ for Cast and Wrought 9-10 Cr Steels

- Examples of cast F/M steel applications:
  - Casting of large T-91 valve bodies for advanced steam cycle power plants.
    - I. Kayigaya, and T. Honda, 1st Int. Conf. on Improved Coal Fired Power Plants, 1988, 1507.
  - Optimization of casting techniques for 9-10Cr steels for steam turbine applications.
Charpy Impact Energy for Electroslag Cast Valve Body Versus Wrought

- The grain size of castings is typically much larger than for wrought products.
- The strength and fracture toughness of a material strongly depend on grain size.
- Advanced investment casting approaches coupled with post-casting heat treatments seek to refine grain size and reduce micro-chemical segregation.
- A sequence of casting + HIP may be the most attractive fabrication route.
RAFM Steel Fabrication Development Schedule - I

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Select Fabrication Route

Not all of the shaded subtasks will be performed.

FW Inv. Casting
- Sub-scale Mockups
- Eval. Properties
- Assess Corrosion
- NDE Specimens
- Full-scale Mockups
- Detailed Prop. Eval.

Grid Inv. Casting
- Sub-scale Mockups
- Eval. Properties
- NDE Specimens
- Full-scale Mockups
- Detailed Prop. Eval.

RAFM Steel Fabrication Development Schedule - II

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Not all of the shaded subtasks will be performed.
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The cost estimates associated with each task in the WBS were based on four primary sources:

- Information from the EU on the overall spending for the current six-year fabrication technology development program.
- Cost estimates from the Japanese TBM program on the estimated cost of fabricating a full-sized first-wall unit for their WCCB.
- Current U.S. costs within the fusion materials program for mechanical property measurements, microstructural analysis and design and evaluation of HFIR irradiation experiments.
- Preliminary estimates of developmental programs with U.S. vendors to develop fabrication solutions to specific U.S. TBM component conceptual designs.

The cost estimates for some tasks were adjusted to account for “known international collaborations”. Reduction factors were applied to the original cost estimates to account for anticipated savings from sharing of research results.
## RAFM Steel Fabrication Development Cost Detail

All costs are $K

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<th>Labor</th>
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Possible Next Steps

- Form Materials/Blanket Fabrication Team (e.g. Kurtz, Rowcliffe, Dagher, Malang, Wong) to prepare a structural material fabrication proposal with more precise dimensional and tolerance information - use Malang/Dagher proposals as reference case.

- Revisit Bodycote - present more detailed proposal on fabrication route.

- Revisit PCC Structural - for more detailed discussion on how investment casting and HIP processing could be combined to fabricate FW - key person, Jim Barrett, not available during first visit.

- Explore hydroforming as a technique for controlling the final dimensions of bent square tubes prior to HIPing with bent panels - many vendors in automotive applications.

- Visit square tube fabrication vendors - Century Tubes, Precision Tube Bending, Bauer Weld and Metal Fabricators.

- Identify vendors experienced in T91 welding - Alstom Power (Jeff Henry), and Euroweld (William Newell) could help narrow the search.
# Current TITAN Task Structure and Budget Allocation

<table>
<thead>
<tr>
<th>Task 1 Transport Phenomena</th>
<th>Subtask</th>
<th>Facility</th>
<th>Budget Allocation, M$</th>
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<td>1-3 Flow control and thermofluid modeling</td>
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*Includes 0.2 M$ for 18J PIE
## Subtask 2-2: Joining and Coating Integrity
- Materials of Interest

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<td>joint specimens with and without coatings to generate He, T, and (He+T)</td>
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<td>1</td>
<td>HIP/diffusion bond, TIG, FSW</td>
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<tr>
<td></td>
<td>SiC</td>
<td>2</td>
<td>NITE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MA957</td>
<td>2</td>
<td>FSW (available material)</td>
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</tr>
<tr>
<td></td>
<td>V-alloy, limited matrix</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dissimilar joint</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F82H-[Be,W]</td>
<td>1</td>
<td>HIP/diffusion bond</td>
<td>see “development needs” below</td>
</tr>
<tr>
<td></td>
<td>9Cr-ODS-[Be,W]</td>
<td>1</td>
<td>HIP/diffusion bond</td>
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<tr>
<td></td>
<td>SiC-[W,F82H]</td>
<td>2</td>
<td>HIP/diffusion bond, flash melt</td>
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<tr>
<td></td>
<td>Cu-[Be,SS]</td>
<td>3</td>
<td>braze</td>
<td></td>
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<tr>
<td></td>
<td>SS-Be</td>
<td>3</td>
<td>braze</td>
<td></td>
</tr>
</tbody>
</table>
Subtask 2-2: Joining and Coating Integrity - Possible Specimens & Irradiation Plan

- **Specimens:**
  - Small specimens: tensile, bend bar variants, TEM, see “development needs” below.
  - Mechanical properties: tensile, fracture, see “development needs”.
  - Microstructural characterization: unirradiated and irradiated base, joint, HAZ as appropriate (TEM), fracture surfaces (SEM).

- **Irradiation Plan:**
  - T diffusion during irradiation, post-irradiation measurement of final profile versus implanted profile, e.g. image plate or nuclear reaction analysis.
  - Post-irradiation annealing to confirm location of He, T.
  - Irradiation in HFIR target rabbit position to modest doses relevant to specific material, ~1 to 10 dpa.
  - Range of temperatures relevant to specific material.
  - Four potential exposure conditions: 1) neutrons only, 2) neutrons + co-implanted He, 3) neutrons + co-implanted T, 4) neutrons + co-implanted He and T.
Subtask 2-2: Joining and Coating Integrity
- Development Needs & Irradiation Costs

- Development Needs:
  - F82H (other RAF/M) to be joining.
  - Alternate testing methods for fracture information from implanted specimens, e.g. indentation techniques.
  - Alternate specimens/testing methods for joint integrity, e.g. shear, torsional, etc.

- Irradiation Costs:
  - Specimen fabrication
  - Neutron charges - currently ~$6k/rabbit/cycle (HFIR evaluating cost structure, possible range is $3 to 11k/rabbit/cycle).
  - Existing gas-gapped rabbit designs for a few small tensile and bend-bar variants
  - Rabbit capsule parts and assembly ~$6 to 10k/rabbit
  - Transport and disassembly ~$3k/rabbit
  - PIE dependent on specimen type and test temperature requirements, ~$5 to 25k/rabbit
    - Less if small, low-dose specimens can be tested outside of hot cell
    - Less if specimens shipped to Japan for PIE
  - ~30 to 50 rabbits, ~$2.5 - 3.5M
Subtask 2-3: Dynamic Deformation - Possible Scientific Objectives

- Measure creep of single-phase monolithic SiC as a function of irradiation temperature, neutron fluence, stress, and crystallographic orientation.
- Determine irradiation creep of fiber constituents for SiC composites.
- Determine irradiation creep of model SiC composites with various engineered interphases to evaluate interfacial shear deformation and its contribution to composite deformation, and develop constitutive models of composite creep.
- Determine influence of n/He, n/T, and/or n/He/T synergism on irradiation creep, swelling, microstructural evolution, and micro-mechanical properties of SiC ceramics and composites.
Subtask 2-3: Dynamic Deformation - Potential Materials Matrix

- Monolithic SiC
  - CVD-SiC.
  - Single crystal SiC, possibly in different orientations.
  - NITE matrix material.

- Fibers
  - Hi-Nicalon™ Type-S, Tyranno™-SA3.
  - Developmental Sylramic™.
  - Graphite fibers (highly and poorly graphitized).

- Composites
  - Unidirectional CVI and NITE.
  - Varied interphase (zero-interphase, PyC, burned).
## Subtask 2-3: Dynamic Deformation - Cost Basis

- Cost estimate done solely for the purpose of illustrating costing basis.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost for 50 rabbits (FY07$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsules (design qualification, parts fabrication, assembly, QA)</td>
<td>500k (10k per rabbit)</td>
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<tr>
<td>Irradiation</td>
<td>630k (3-11k per rabbit-cycle, 6k x 1.5 average cycles assumed)</td>
</tr>
<tr>
<td>Transport, disassembly</td>
<td>150k (3k per rabbit)</td>
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<tr>
<td>Samples (procurement, fabrication, and machining)</td>
<td>300k</td>
</tr>
<tr>
<td>PIE (measurement, passive thermometry, TEM/SEM for selected samples, LAMDA support)</td>
<td>500k (10k per rabbit)</td>
</tr>
<tr>
<td>Total</td>
<td>$2.1M (~2.3M with 3% annual inflation and flat profile)</td>
</tr>
</tbody>
</table>