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Revision 0

In-cell Thermal Creep Frames for Demonstration Project Preparations

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EXECUTIVE SUMMARY

The thrust of advanced nuclear reactor demonstrations demands the accelerated qualification of in-core materials to enable licensing processes and developing the performance data. Due to the high-operating temperatures of such reactors, long-term mechanical behavior under constant load is essential to determine the geometrical and mechanical integrity of in-core components during operation and off-normal conditions. Therefore, the thermal creep behavior of neutron-irradiated advanced reactor materials must be determined. The feasibility of using subsize specimens for the irradiation campaigns and the limited available infrastructure challenge the assessment of thermal creep behavior of advanced reactor materials. Therefore, the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) National Reactor Innovation Center (NRIC) prioritizes the development of a thermal creep testing infrastructure for multiple subsize specimens to accelerate the demonstration and deployment of advanced reactor concepts. This report describes the activities for the construction of a thermal creep testing capability at Idaho National Laboratory (INL). The overall project consists of conceptual design, out-of-cell demonstration, and in-cell demonstration phases.

During fiscal year (FY)-2021, the team finished the conceptual design of a thermal creep test facility that can test multiple subsize specimens. This conceptual design consisted of the determination of technical and functional requirements, the determination of the design space, and the preparation of the technical drawings. Technical and functional requirements were categorized as required and desired capabilities and the conceptual design was performed to meet all the required capabilities with the flexibility to achieve the desired capabilities. The design space identified the operational capacity of the creep frame for different advanced reactor relevant materials with the consideration of the feasible operation in the hotcell at the Fuels and Applied Science Building (FASB) at INL. Based on the requirements and design space, the multiple specimen creep frame was designed. The official INL engineering drawing process was started and the procurement of materials for construction was initiated. For FY-2022, the out-of-cell demonstration and final installation of the multiple creep frame is planned.

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ACRONYMS

ASTM	American Society for Testing and Materials
CAD	computer-aided design
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
FASB	Fuels and Applied Science Building
FY	fiscal year
HFEF	Hot Fuels Examination Facility
IASCC	irradiation-assisted stress-corrosion cracking
INL	Idaho National Laboratory
IPT	integrated priority list
LABE	laboratory electronic notebook
LMP	Larson-Miller parameter
LVDT	linear variable differential transformer
MFC	Materials and Fuels Complex
NRIC	National Reactor Innovation Center
YS	yield stress

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1. INTRODUCTION

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE) National Reactor Innovation Center (NRIC) prioritizes the development of a thermal creep testing infrastructure for multiple subsize specimens to accelerate the demonstration and deployment of advanced reactor concepts. This report describes the activities for the construction of a thermal creep testing capability at Idaho National Laboratory (INL). The overall project consists of conceptual design, out-of-cell demonstration, and in-cell demonstration phases.

The current momentum of the advanced reactor development requires accelerated materials qualification for licensing and final deployment of these reactors. Since these reactors operate at temperatures above 500°C, the core internal components—including the fuel cladding alloys—must exhibit excellent geometrical stability and mechanical integrity for increased long-term operation. Therefore, the high-temperature and long-term mechanical integrity of in-core components must be assessed to progress materials qualification for advanced nuclear reactors.

Advanced steels and refractory alloys are mainly considered as structural materials for the advanced reactor concepts, and the structural materials in these systems experience higher irradiation damage as compared to the structural components of conventional light-water reactors. The operating temperature window of structural materials in advanced reactors is constrained between the radiation embrittlement and thermal creep. As depicted in Figure 1, the materials performance is to be governed by the thermal creep behavior above 500°C. Therefore, the thermal creep advanced reactor materials must be assessed for qualification purposes. Thus, the determination of engineering level creep parameters, such as the onset of tertiary creep, fracture time, and Larson-Miller parameter (LMP) is critical, as well as the steady-state thermal creep parameters.

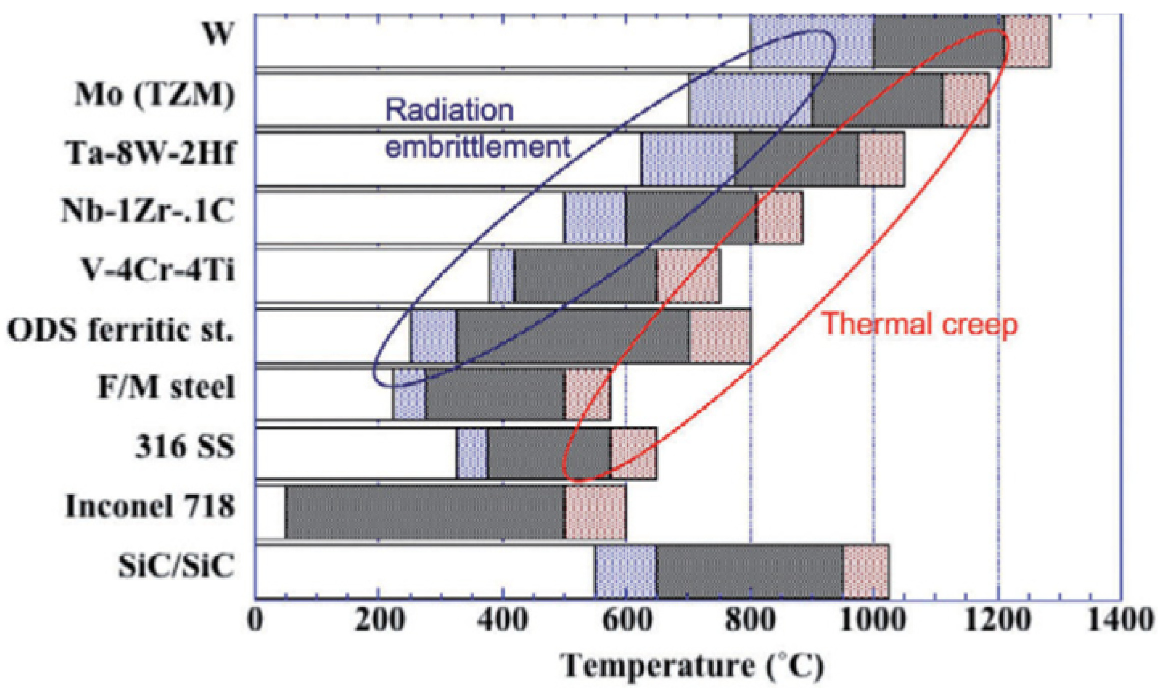

Figure 1. Operating temperature window of structural materials in advanced reactor concepts [1].

Conventional thermal creep tests are performed based on the American Society for Testing and Materials (ASTM) International Standard. Since creep testing takes a long time, these tests are often performed using a variety of samples with multiple independent creep systems. While the ASTM standard is developed to generate reliable and reproducible data, the large specimen geometry challenges testing of neutron-irradiated samples due to handling of radioactive material where specialized facility like a hotcell is needed to perform testing. As the specimen geometry increases, the footprint of the equipment increases as well, eliminating the potential for multiple specimen testing in restricted and remote environments. Physical space is limited for neutron exposure experiments, making the use of ASTM standard sized samples incredibly restrictive. Additionally, common irradiation capsules aim at subsize specimens to maximize the number of specimens. Therefore, flat sheet/plate uniaxial tensile specimens, as observed in Figure 2, are preferred rather than cylindrical ASTM tensile bars for irradiation campaigns. Thus, performing conventional creep tests becomes unfeasible on the available irradiated specimens. Currently, there is no infrastructure to perform thermal creep on subsize specimens. A facility that uses multiple specimens to perform thermal creep is needed to address the needs of maximizing the number of specimens, and thus, accelerating materials testing. To overcome infrastructural challenges, NRIC has supported the construction of multiple specimen creep frames located in facilities at INL.

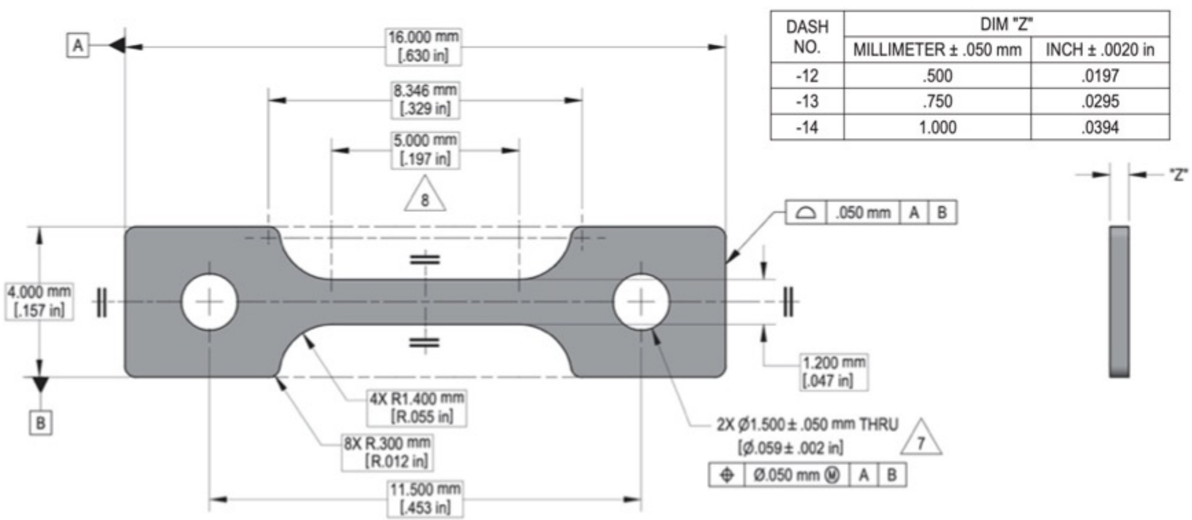

Figure 2. Subsize specimen design (INL drawing: DRW-606738).

This report describes the activities related to the construction of an in-cell thermal creep test facility for small-scale specimens in the irradiation-assisted stress-corrosion cracking (IASCC) hotcell located at the Fuels and Applied Science Building (FASB) at INL. The whole project includes three stages: (i) conceptual design; (ii) out-of-cell demonstration tests; and (iii) in-cell demonstration testing. During the current fiscal year (FY)-2021, the conceptual design of the creep test facility has been completed, the official drafting process of drawings has been initiated, and the procurement of the materials and equipment has been started.

2. CONCEPTUAL DESIGN

Conceptual design of the subsize specimen creep frame was separated into three primary activities: (i) the determination of the required and desired capabilities; (ii) the identification of a design space for the experimental concept; and (iii) the production of a conceptual design.

2.1 Determination of the Required and Desired Capabilities

Technical and functional requirements of the in-cell creep frame were discussed in detail. Considering the space availability in the hotcell, required and desired capabilities were identified. Required capabilities identifies the minimum requirements to achieve success while desired capabilities identify the maximum success if achievable.

Required capabilities were determined as:

- The capability of controlling temperature within ± 5°C or better.
- Performing creep test in the temperature range of 600–800°C.
- The use of individual creep frames, where multiple independent creep frames will be inserted into the hotcell.
- Applying load via dead weights directly beneath the load train considering the space limitations in the hotcell. Maximum dead weight was determined to be a total of 100 lbs. due to the manipulator lifting capabilities and hotcell dimensions.
- The determination of the rupture time using a proximity or displacement sensor.
- No permanent deformation in the loading train and the sample fixturing.
- Functionality of the utility cell must remain intact.

Desired capabilities were determined as:

- The measurement of the creep strain with a high accuracy using non-contact optical techniques or linear variable differential transformer (LVDT).
- The capability of controlling temperature within ± 3°C or better.
- Performing creep testing within the extended temperature range 400–1000°C.
- Ability to load or unload samples in the middle of the test.
- Ability to quench (or cool rapidly) tested specimens just after the test to lock the crept microstructure.

2.2 Design Space for the Creep Experimental Concept

The design space of the in-cell creep frame was identified using the yield strengths (YSs) of various advanced reactor candidate materials. The maximum applied load was compared to the percentage of alloy YS at various temperatures, as shown in Table 1 and Table 2. The stresses were calculated based on the subsize specimen design, as shown in Figure 2, which has a specimen thickness of 1 mm.

Table 1 shows the creep frame capability at 40% of the YS of a variety of alloys in a temperature range of 600–1000°C. The green-filled areas represent testing conditions that the creep frame can perform tests for a given alloy at a specific temperature. The number corresponding to the temperature and the alloy represents the applied stress at 40% of the YS of the alloy at that temperature. The same format applies to Table 2, except that the applied stress is at 70% of the YS. At the stress level of 40% of the YS, all alloys, except Alloy 718, can be tested using the creep frame at the low end of the proposed testing temperature range of 600°C. The creep frame can also be operated at a lower percentage of YS values than 40% of the YS, which enables the frame to test many alloys. Due to the high strength and creep resistance of Alloy 718, it is used to make the load train and sample fixtures.

As the applied stress increases to 70% of YS, alloys such as x-750, 12 YWT, and 725 cannot be tested at 600°C. Additionally, Alloys 725 and x-750 cannot be tested at 700°C. On the other hand, the specimen thickness is an important factor affecting the applied stress. If the specimen thickness is reduced to 0.5 mm, the creep frame can perform tests on all alloys in the list at 70% of the YS, as shown in Table 3.

2.3 Conceptual Design

Prior to the start of the conceptual design, a sketch of the IASCC hotcell facility at FASB was prepared to evaluate the available space. These sketches were prepared based on the official technical drawings of the utility cell and known dimensions of the existing equipment in the utility cell portion of the IASCC hotcell, as seen in the computer-aided design (CAD) sketch shown in Figure 3. The technical drawings of the utility cell are included in the laboratory electronic notebook (LABE), "Subsize specimen creep test capability for FASB (LABE-141)."

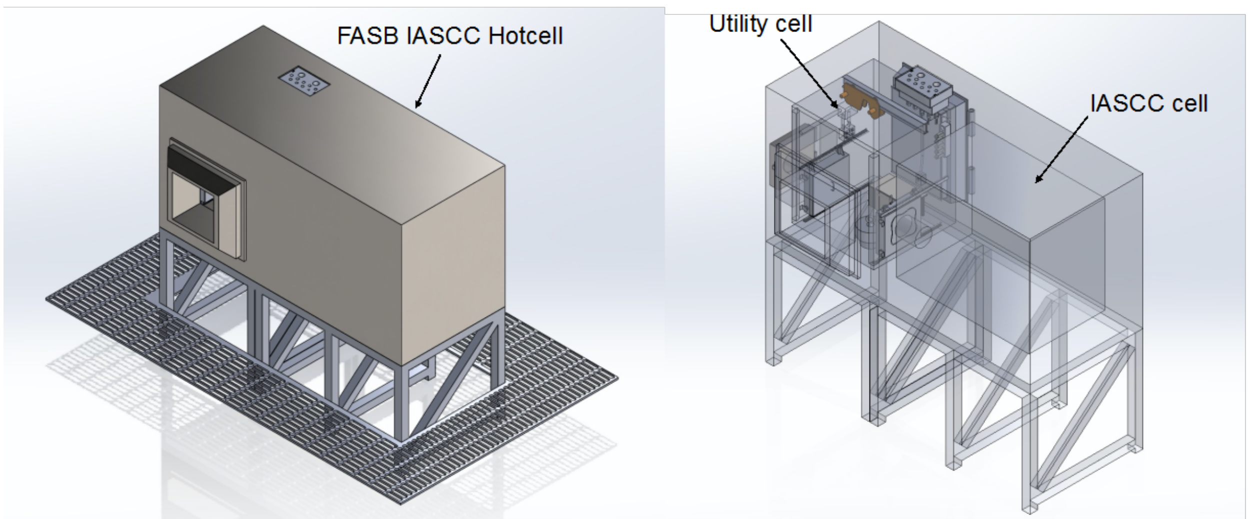

Figure 3. CAD sketches of the IASCC hotcell showing the utility and IASCC cells.

Figure 4(a) shows a photograph of the actual utility cell, while Figure 4(b) provides the CAD sketch. In the sketch, manipulators and the microscope are not included, as shown in Figure 4(a). The current microscope will be replaced by the multiple specimen creep frame, while the creep equipment will be put on top of the table as shown in Figure 4(b). Because the role of the utility cell will be to support activities related to the IASCC cell, the multiple specimen creep frame should not hinder utility cell operations.

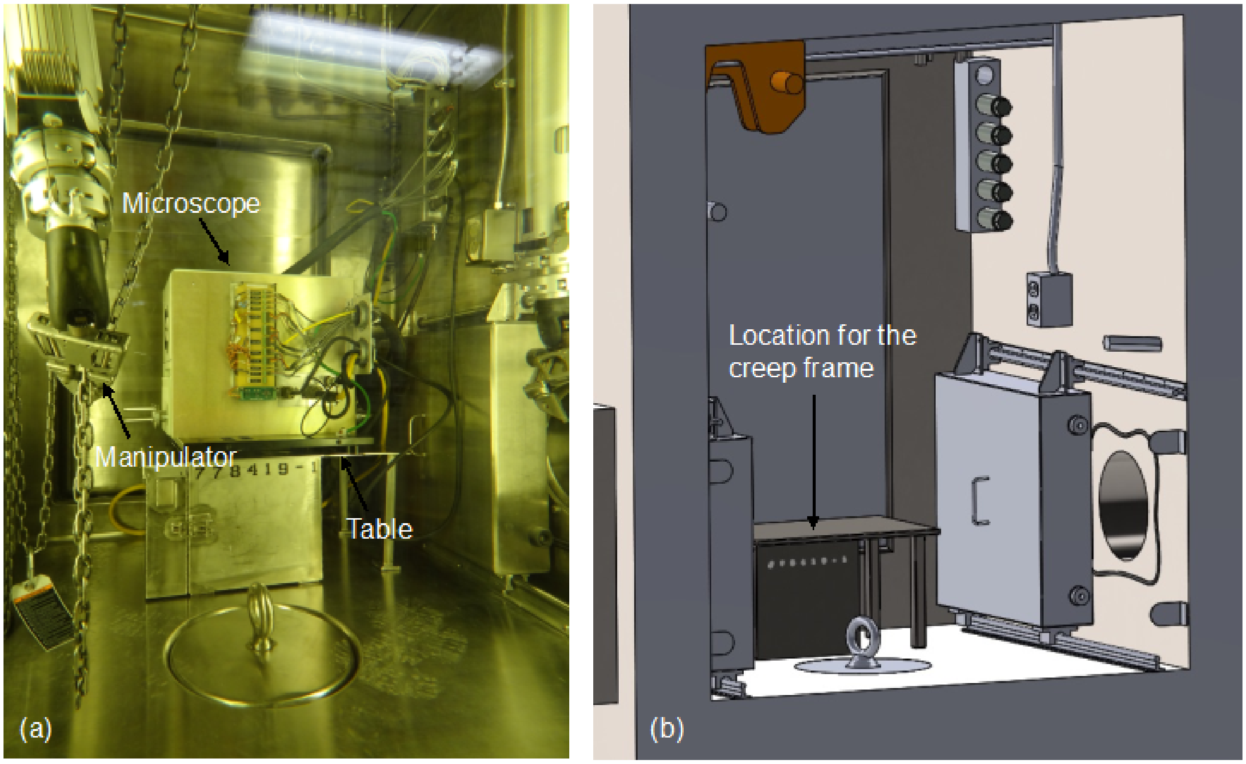

Figure 4. (a) Photograph of the utility cell. (b) CAD sketch of the utility cell showing the location for the creep frame.

Figure 5 shows the conceptual creep apparatus for a single specimen. The subsize specimen is inserted into the drop-in fixtures. The upper load train is also inserted into a ball-joint clevis, and the ball-joint clevis is bolted to a top crossbar, as shown in Figure 6. The lower load train is directly attached with the dead weights to apply the stress. Based on the manipulator dexterity, the maximum value of a single dead weight is set to 15 lbs. (e.g., 6.8 kg). Weights lower than the maximum allowable also will be used for fine-tuning. Appendix A provides a larger look at the subsize specimen drawing.

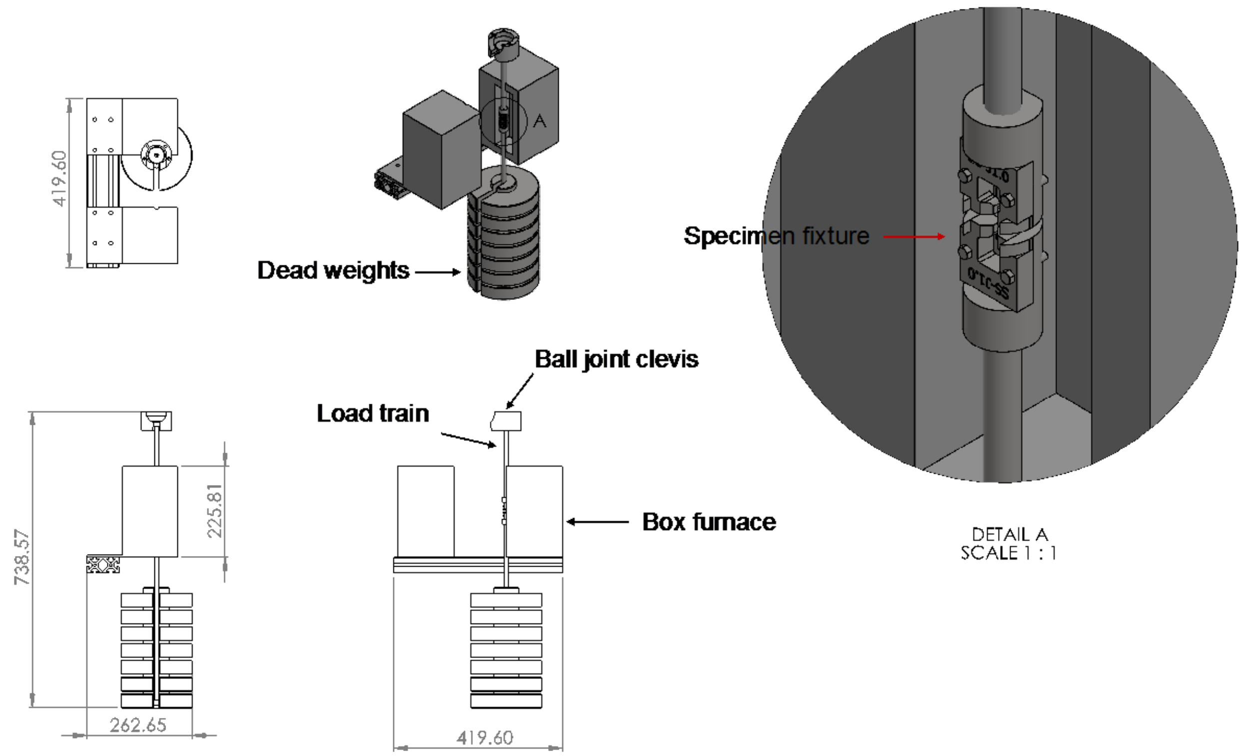

Figure 5. Design of a single creep apparatus for subsize specimen geometry.

A three-zone box furnace will be used to heat the subsize sample and fixturing. The LABE for the specs and the quote for the MTS box furnace provides more information. The box furnace will have two-degrees of freedom: (1) it will slide laterally; and (2) it will rotate around a pivot to ease in manipulator operation. One critical parameter for creep testing is the temperature measurements. Because of the restricted and remote operation in a hotcell, a robust technique that is exercised in the hotcell at the Materials and Fuels Complex (MFC) Hot Fuels Examination Facility (HFEF) will be adapted as follows. Temperature measurements are performed using an instrumented specimen to determine the temperature gradient along the axial direction of the specimen and the corresponding load train in the furnace. A constant temperature offset is determined for the three furnace temperature zone controllers (e.g., top, middle, bottom) for the desired test temperature. Then, these offsets are used to set the temperature of the zone controllers for the non-instrumented samples.

Figure 6 shows the conceptual design of the multiple creep frame for the three-specimen testing capability and the footprint of the equipment. The creep frame spans a space determined by height and two sides of 1165.21 mm, 476.25 mm, and 825.50 mm, respectively. The overall maximum volume is 0.458 m^3. The creep apparatus will be bolted to the top crossbar as shown in Detail A. Jackpots will be used beneath the dead weights to avoid any uncontrolled fall. The design ensures that manipulators can also reach out to each creep apparatus with minimum restrictions.

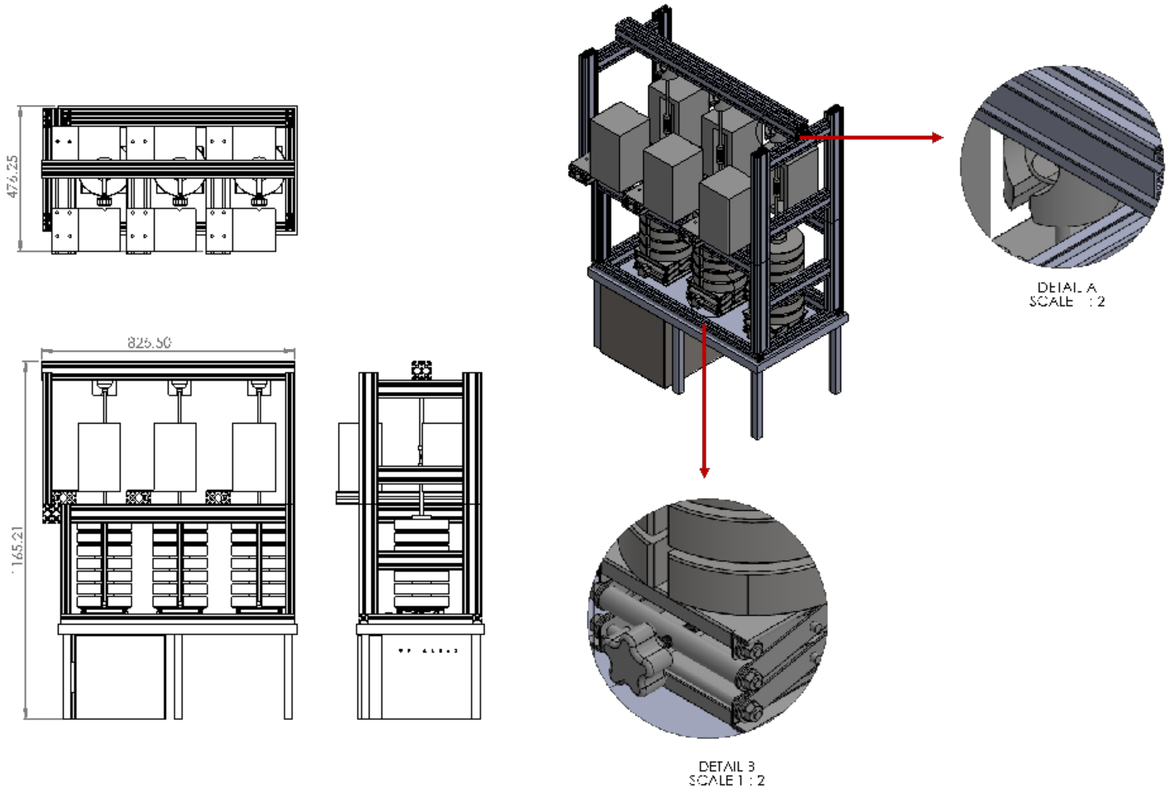

Figure 6. Conceptual design of the multiple sample creep frame. Detail A shows ball-joint clevis attachment to the main crossbar. Detail B shows the jackpot arrangement to sustain weights.

Figure 7 shows the schematic of the utility cell where the multiple specimen creep frame is installed. The distance between creep frames is arranged not to restrict the utility cell operations. The utility cell's transfer door and plug operations are kept intact.

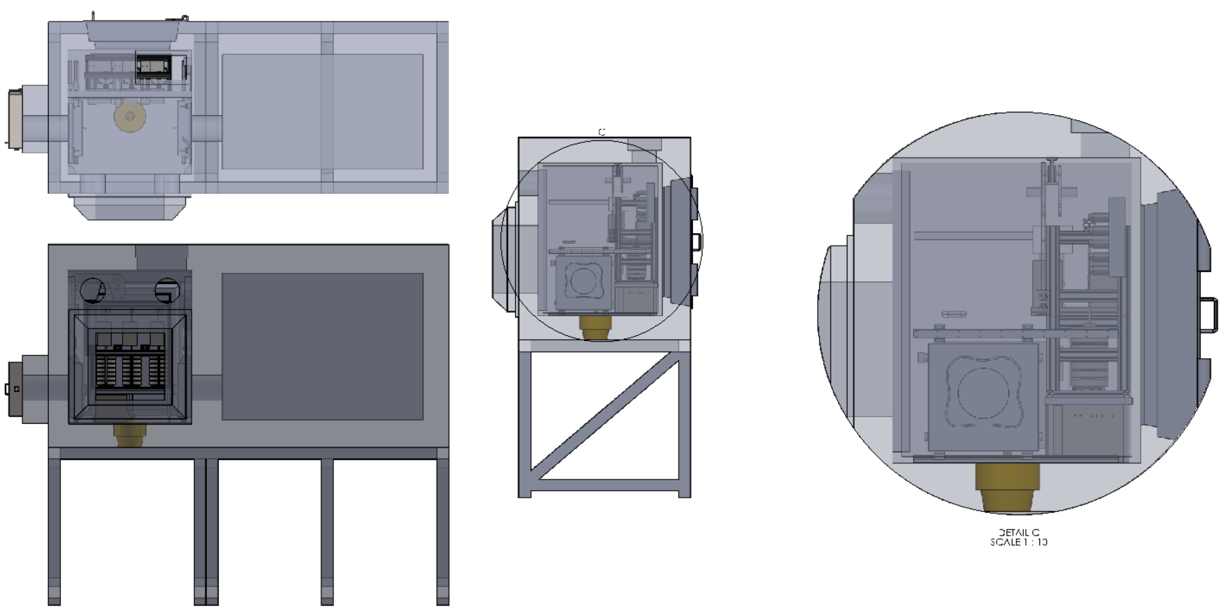

Figure 7. The IASCC hotcell sketch showing three creep frames located in the utility cell, Detail C shows the physical location of the multiple specimen creep frame compared to the hotcell transfer doors and

plug.

3. CONCEPTUAL DESIGN

The conceptual design of the multiple creep frame was performed in FY-21. During FY-22, the following activities are planned: (i) the construction of a functioning creep frame for out-of-cell demonstration experiments; (ii) the identification of the facility needs and work controls for the in-cell installation; and (iii) the installation of the creep frame in the IASCC utility cell at FASB.

4. SUMMARY

During FY-21, the conceptual design of an in-cell, multi-sample creep test facility was completed. Firstly, the technical and functional requirements were identified. These requirements were categorized as required and desired capabilities. The conceptual design was performed to meet all the required capabilities with the flexibility to achieve desired capabilities. Secondly, the design space of the creep frame was identified for a 1-mm-thick specimen as a function of selected fast reactor alloys, applied stress, and the test temperature. Based on these parameters, the operational boundary of the creep frame was identified for the maximum stress levels of 70% YS of a particular alloy within the temperature range of 600–1000°C. With the use of a thinner specimen, the operational space of the creep frame was significantly extended. Finally, the conceptual multiple creep frame was designed using direct dead weight loading and three-zone box furnace. the CAD drawing of the multiple sample creep frame was placed into the pre-sketched hotcell, including existing equipment. The conceptual design ensured the original functionality of the hotcell was unchanged. The official engineering drawing process was started and the procurement of materials for construction was initiated as well.

5. REFERENCES

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Appendix A –
Subsize Specimen Drawing

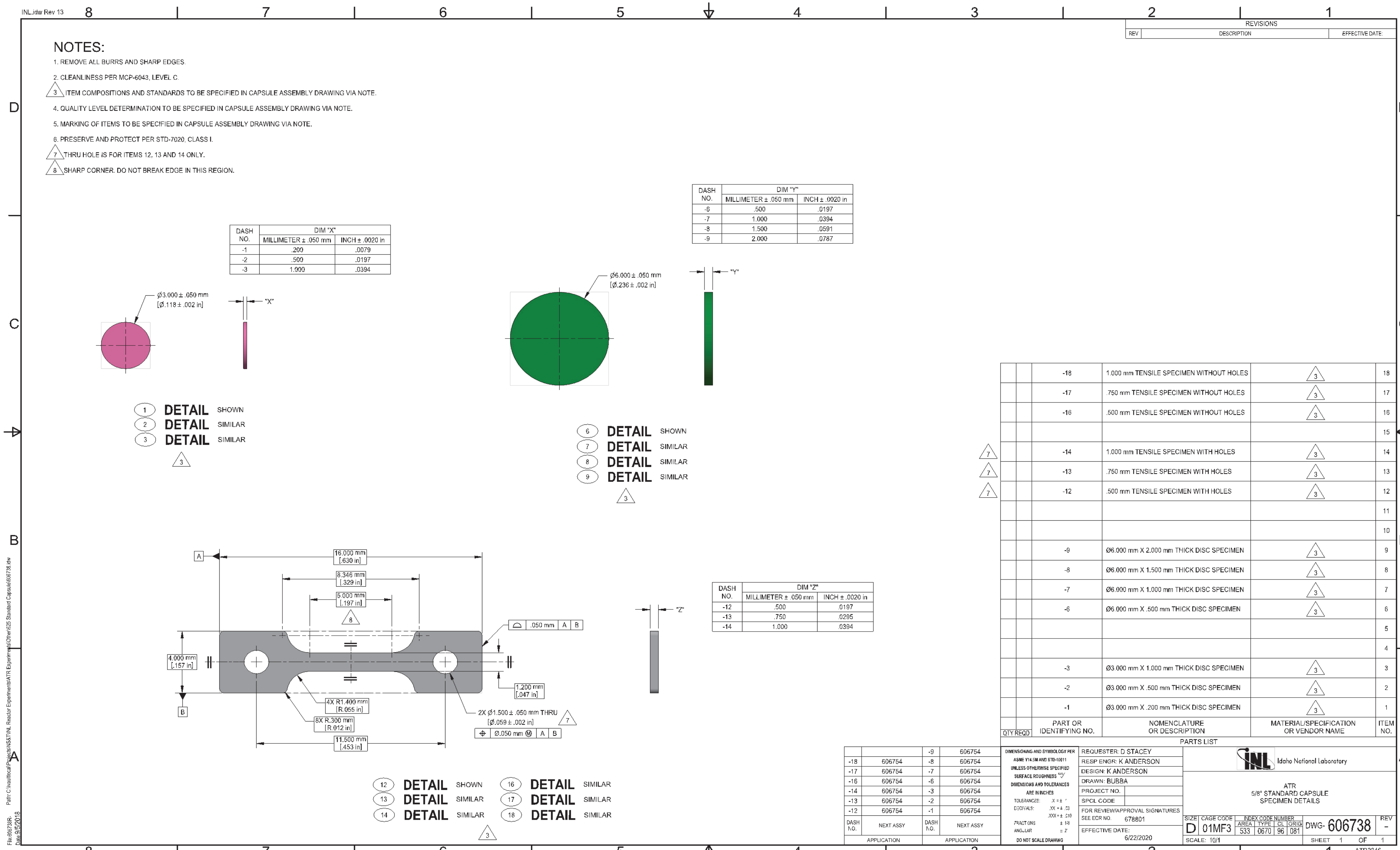

Figure 8. Subsize specimen drawing. The design of the subsize specimen was supported by the INL MFC integrated priority list (IPL) funding: “Comprehensive Mechanical Testing Capability.”