INL/RPT-24-81118
Revision 0

Enabling Digital Image Correlation for Deployment in the Hot Fuels Examination Facility

Advanced Fuels Campaign

SEPTEMBER 2024

Robert S. Hansen, Philip G. Petersen, Prasenjit Dewanjee,
Jake A. Stockwell, David W. Kamerman, Fabiola Cappia

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

Page intentionally left blank

INL/RPT-24-81118
Revision 0

Enabling Digital Image Correlation for Deployment in the Hot Fuels Examination Facility

Robert S. Hansen, Philip G. Petersen, Prasenjit Dewanjee, Jake A. Stockwell,
David W. Kamerman, Fabiola Cappia
Idaho National Laboratory

September 2024

Idaho National Laboratory
Originating Organization
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

ABSTRACT

Digital image correlation (DIC) is a non-contact image-based technique for displacement and strain measurement. It is also a full-field method that can provide excellent spatial resolution. DIC has been widely used for measurements in many styles of mechanical tests and is desirable in part because of this flexibility to measure nearly any material across a range of time and length scales. Its ability to measure localized strain for tests and in environments not accessible to other strain measurement techniques makes it an ideal option for several mechanical test cases that exist in hot cell facilities such as the Hot Fuel Examination Facility (HFEF) at the Idaho National Laboratory (INL). However, DIC has not been demonstrated at HFEF, and several barriers to implementation in the hot cell environment exist. This report outlines the possible paths for deploying DIC at HFEF, weighing the technical advantages and risks with each path. It also discusses the steps which must be taken to add this capability to the suite of post-irradiation examination (PIE) techniques available at HFEF. Finally, it concludes with recommendations for the best method to perform DIC at the facility.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

ASTM	American Society for Testing and Materials
ATF	accident tolerant fuels
DAQ	data acquisition system
DIC	digital image correlation
EC	engineering change
EQP	equipment qualification procedure
HFEF	Hot Fuels Examination Facility
INL	Idaho National Laboratory
LED	light-emitting diode
LWR	light water reactor
MFC	Materials and Fuels Complex
PIE	post-irradiation examination
USB	universal serial bus
USQ	unanswered safety question
VAC	volts alternating current
VRO	variable ray origin

Page intentionally left blank

Enabling Digital Image Correlation for Deployment in the Hot Fuels Examination Facility

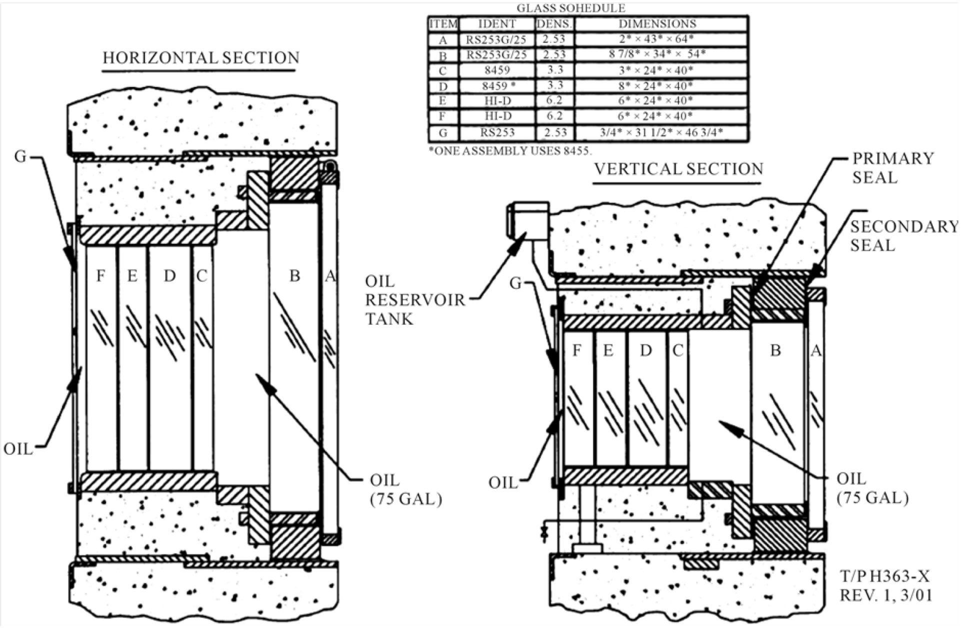
1. INTRODUCTION AND BACKGROUND

Digital image correlation (DIC) is a non-contact image-based method used to measure full-field displacements and deformation on the surface of a material under mechanical or thermal loading. Images of the surface are taken before, during, and after some deformation, and an algorithm is used to track subsets of pixels from image to image [1]. The result is a point-wise displacement field, which can be used to calculate full-field strains. DIC can either use a single camera for in-plane measurements or use two cameras positioned at some angle (stereo DIC) to enable measurement of three-dimensional surfaces and out-of-plane displacements. It offers advantages over traditional strain measurements like strain gauges or extensometers, which must be physically attached to the specimen and are limited to a one-directional strain value averaged over an entire area. DIC is non-contact and can capture heterogeneous strains across the specimen, better measuring localized deformation. It can be adjusted to various time and length scales by implementing different optics for the image capture, providing significant flexibility in applications. When used as a part of mechanical or thermal experiments, it provides rich data sets that would be otherwise inaccessible.

Experimental applications of DIC are seemingly endless, ranging from novel coefficient of thermal expansion measurements [2], [3] to high accuracy fracture and fatigue testing with crack propagation monitoring [4] to characterization of functionally graded materials [5]. This technique is well-suited for application in hot cells: the non-contact nature of the method is ideal for remotely handled irradiated materials. Because DIC results take the form of data-rich full-field deformation maps, they allow a direct comparison predicted behavior for model validation [6], [7]. DIC can also easily handle tests with non-traditional geometries [8], [9]. This could be particularly useful with post-irradiation examination (PIE) of irradiated fuels or in-core components, where making specimens following the American Society for Testing and Materials (ASTM) standards is challenging or impossible, requiring the use of non-standard specimens [10], [11]. It is expected that implementation of DIC for use in the Hot Fuels Examination Facility (HFEF) at Idaho National Laboratory (INL) will enable high-fidelity strain measurements for various new and existing mechanical tests of irradiated materials.

The specific tests which may benefit from this DIC capability are varied. However, the immediate application of testing accident tolerant fuel (ATF) cladding concepts for light water reactors (LWRs) will be the focus of this report. These test requirements help define the operational envelope needed for DIC to be successful. The curved surface of the cladding will generally be the surface under investigation with DIC, requiring stereo DIC with two cameras. As part of the stereo DIC process, a calibration phase must be completed in which images of a known calibration target are taken with each camera, which allows triangulation of the cameras and determination of stereo DIC parameters. Tests may require different fields of view, ranging from a few inches (e.g. the area of interest in an internal pressurization tube test [12], [13]) to a quarter of an inch (e.g. the gauge size of a ring tension test [11], [14]). Additionally, magnitudes of strain experienced during the test are expected to range from very small, on the order of 0.04-0.06% for SiC proportional limits [15], to much larger, on the order of 20% for metallic claddings to failure strains [16]. These expected experimental conditions should be considered in determining required optical magnification and strain resolution of a potential DIC in-cell system, and a stereo DIC system rather than a single camera is considered in the remainder of this report.

A major requirement for DIC is optical access to the material of interest. While this is straightforward for out-of-cell testing, the hot cell environment requires imaging equipment to be placed either (a) inside the hot cell or (b) outside and aimed through one of the hot cells shield windows. If the optics are placed within a hot cell such as the main cell in HFEF, they must be protected or shielded from damaging radiation fields. Additionally, adjusting imaging settings becomes significantly more challenging when it must be performed in the hot cell, further limiting the flexibility. If instead, imaging is performed through the window with equipment placed outside, the challenges of long working distances and imaging distortions through the highly refractive shield windows (see Figure 1) must be overcome. The purpose of this report is to discuss the advantages and challenges associated with each of these two options. To assess the feasibility of both methods, the path forward and work needed to achieve DIC measurement in the HFEF hot cell is also outlined. Hurdles which must be cleared for either method to be effectively implemented are discussed, along with a short discussion on other methods not included in full consideration for this report. Ultimately, a final recommendation is given for the preferred path to enable in-cell DIC.


GLASS SOHEDULE

ITEM	IDENT	DENS.	DIMENSIONS
A	RS253G/25	2.53	2* × 43* × 64*
B	RS253G/25	2.53	8 7/8* × 34* × 54*
C	8459	3.3	3* × 24* × 40*
D	8459 *	3.3	8* × 24* × 40*
E	HI-D	6.2	6* × 24* × 40*
F	HI-D	6.2	6* × 24* × 40*
G	RS253	2.53	3/4* × 31 1/2* × 46 3/4*

*ONE ASSEMBLY USES 8455.

Figure 1. Diagram of a typical multi-pane window at the HFEF hot cell. (This window consists of six panes of leaded glass with varying densities, and several layers of oil [10].)

2. VIEWING THROUGH THE WINDOW

One of the options for enabling DIC measurements of irradiated cladding and other materials within the hot cell at HFEF is to place the optics outside the cell and image through the window. Generally, this option allows better access to the optics for fine-tuning adjustments and eliminates shielding of optics. However, to enable this type of measurements, there are some technical barriers which must be addressed. Some tools have been developed for other DIC applications which face similar barriers (for example, imaging materials submerged in water [17]), but imaging through the hot cell window consists of a unique combination of several barriers. In the sections below, the advantages and disadvantages of this potential method are presented in greater detail, followed by the proposed path to implementation.

2.1. Through-Window Method Advantages

A primary reason for imaging through the window is to prevent degradation of cameras and optics. The high-activity alpha/gamma main cell in HFEF is a very harsh environment for electronics, and any cameras sent in-cell will have a much shorter usable life than the same components if used only out-of-cell. The exact lifetime of in-cell sensors and other electronic components of the camera would be dependent on shielding used and location-specific radiation fields. Additionally, radiation would gradually degrade the optical lenses paired with the camera sensors [18]. Keeping all optical equipment out of the hot cell eliminates any potential radiation effects and subsequent equipment degradation, which reduces downtime and eliminates potential sources of error and uncertainty. It also reduces significantly the engineering design time, effort, and cost for developing shielding that would be otherwise needed to protect the sensitive equipment in an effort to extend equipment lifetime.

The placement of cameras and lenses outside the window also improves the flexibility of the setup. For DIC measurements, there are many physical parameters which should be controlled to optimize a single setup and reduce measurement errors. These may include but are not limited to aperture, stereo angle, lens position, focus, and working distance [19]. Adjustments of these parameters must be balanced against others. For example, focus should be set while the aperture is fully open, but after focusing the aperture is usually adjusted again to improve depth of field. This in turn affects the lighting and exposure time settings, which generally requires iterative adjustments. In addition, different test applications will require different fields of view, which means switching the setup. This is accomplished through changes in working distances, lens modifications (such as adding doubler tubes), lens changeouts, or adjustment of lens settings for special zoom lenses. A single researcher would be able to quickly adjust these settings in a fraction of the time it would take operators to make the same adjustments with remote manipulators, and no additional engineering modifications are needed for such remote operations. This would reduce time, cost, measurement uncertainty and improve DIC measurement quality. It also would allow higher throughput at the load frame in the hot cell facility, reducing the duration of an individual test campaign and freeing up both window and operator time for other projects.

To allow general positioning and fine-tune adjustability of these physical parameters of cameras and lenses, specialized fixturing would need to be designed for remote operation. Because such a placement and adjustment system would be placed in-cell and would likely be complicated, it would require additional engineering design effort. This would be further complicated by the need to interface with any shielding used to isolate the camera and lens from radiation while allowing access. It is also expected that the fully designed system would need to undergo the engineering change (EC) and equipment qualification procedure (EQP) processes required of such in-cell systems at INL, with their accompanying paperwork. This would increase time to deployment and associated costs, while also reducing impact on the safety basis of the facility and eliminating unanswered safety question (USQ) reviews. Avoiding these challenges is a clear advantage of through-window measurement.

Another advantage to placing equipment outside is it avoids the use of any cell wall data, power, or other feedthroughs. Typical cameras used for DIC utilize universal serial bus (USB) or ethernet connections, and sometimes require a custom power supply as well. For high speed or dynamic applications that require precise image triggering, a data acquisition system (DAQ) or other triggering hardware (including trigger signal cables) are also needed. If cameras were placed in-cell, additional engineering efforts would be needed to design customized pin connections through existing feedthroughs, and potential noise and signal loss in cabling would need to be accounted for. Placing cameras and lenses outside the cell window circumvents these issues, reducing engineering time and cost, allowing more flexible solutions at lower cost and with less effort.

The placement of cameras outside also reduces the waste generated within the hot cell. Cameras, lenses, and other DIC equipment placed inside the hot cell must be considered disposable because of the short lifetime in the damaging radiation environment. The cost of replacement is much lower for out-of-cell placement and reduces the labor and disposal costs associated with generating waste inside the hot cell. If a camera, lens, or other component does need to be replaced, it is much easier and faster to do so out of cell than in-cell. Additionally, the through-window method can be easily deployed at other windows of the main cell or decontamination cell at the facility. This provides further flexibility for DIC measurements at any window where deformation/displacement measurement is desired, such as measuring thermally induced strains. An in-cell system would be designed to interface with a specific benchtop or equipment environment of a single window, requiring some degree of redesign for each new window, potentially including wall feedthroughs. Any further redesign carries with it the likelihood of additional cost and time for implementation. Conversely, a setup with camera and lens placed outside the cell would interface with the same window design and geometry, allowing deployment to other windows with no additional redesign.

2.2. Through-Window Method Challenges

Although there are several advantages to keeping the optics outside of the cell and imaging through the shield window, challenges also exist for this method. One of the most obvious is that the setup of the cameras and lenses outside the window has the potential to get in the way of operators using the remote manipulators at the window. General standard practice is to keep the area in front of the window clear from other obstacles/equipment not needed to allow full range of motion of the remote manipulators. Although there are ways to minimize the profile of the imaging setup (discussed in the following section), it is still a challenge that should be considered.

To accomplish this, a mounting system would need to be designed. This mounting system would need to be rigid without becoming a permanent part of the window, to minimize obstruction of the window when not in use and to avoid the EC/EQP process that might be required if it was to become a permanent fixture of the hot cell. However, if it is non-permanent it is inherently at risk of being bumped or inadvertently moved after stereo DIC calibration is performed either before or during a test. This will likely require a mounting system which is rigid once set up and frequent system calibration or verification, likely daily during the testing campaign.

One of the key challenges to through-window imaging is the refraction effect of the thick windows. As shown in Figure 1, a typical window in use at the HFEF hot cell at INL consists of several layers of leaded glass separated by mineral oil [20]. As rays of light pass through the window, they bend at each interface of materials with differing refractive indices. The result is a tortuous path of transmission, leading to refractive distortions in the image and preventing accurate DIC measurement by traditional means. This is exacerbated by the non-perpendicular angles required for stereo DIC, as a greater incident angle causes a greater change for the angle of refraction. Such refraction must be accounted for in the calibration scheme of the DIC software or corrected after the fact, although such corrections would be complex and very positionally dependent.

Related to the refraction challenge is the dispersion effect. While the window materials have high refractive indices which redirect the angle of transmitted light, they can refract different wavelengths of light at different angles. Just as a prism separates light by wavelength, these window materials cause light to separate into different colors. This effect can be seen in Figure 2, where the image through the hot cell window shows a visible separation between red and blue wavelengths at capsule edges. This wavelength-dependent variation in refractive index, called dispersion, can reduce the optical clarity of the transmitted image. At the magnifications needed through the windows, this causes visible blurring of the specimen images, preventing effective DIC measurements.

Figure 2: Image of a graphite capsule, taken through a window at the HFEF hot cell [21]. The dispersion effect is visible, with separation between red and blue wavelengths noticeable at the capsule edges.

Figure 3 shows images from preliminary testing with long-range lenses at a working distance and stereo angle typical of through-window DIC. One image set is taken through air where no dispersion occurs (A and D), and two others are taken through a series of water-filled glass tanks where dispersion is evident (B, E, C, F). Even though the images are monochrome, the camera sensors still capture all the visible wavelengths of light, and so dispersion results in blurriness of the image. In image E, there is increased blurriness in the horizontal direction (the calibration dot edge is crisper at the top and bottom). This highlights the effect of the dispersion, as the incident angle is also aligned horizontally with the two cameras placed side-by-side. If instead the cameras were stacked on top of each other with a vertical stereo angle, the most blurred parts of the calibration dot would be at the top and bottom. The effect is pronounced in image F, where the speckle pattern is blurred, and individual speckles are seemingly stretched in the horizontal direction. To get clear images for DIC calibration and speckle pattern correlation, the dispersion effect must be addressed.

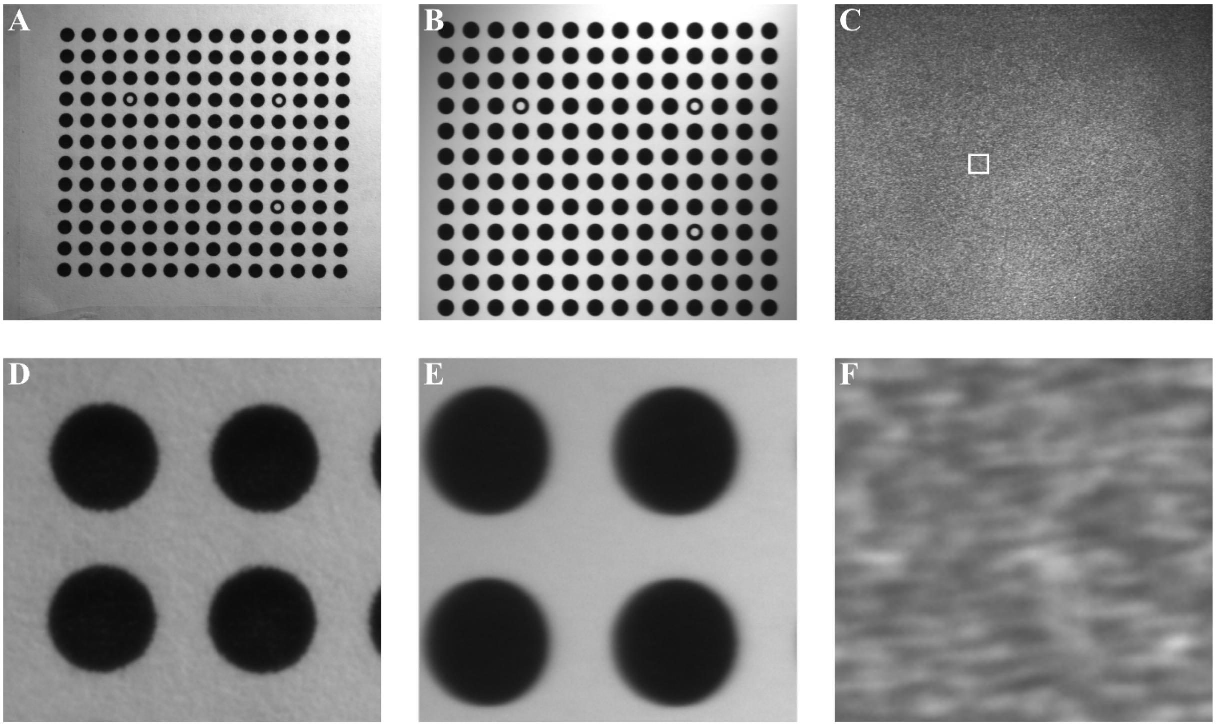


Figure 3: Effect of dispersion viewing at working distance of roughly 10 feet. A and D: calibration plate imaged through air; B and E: calibration plate imaged through a series of water-filled tanks; C and F: fine speckle imaged through a series of water-filled tanks. Bottom row is higher magnification of top row.

Another challenge for through-window imaging is the lighting. Due to the thickness of the window shown in Figure 1, there will be significant transmission losses resulting in less light reaching the camera. This can be accounted for in a variety of ways, including aperture settings, exposure time, and increased brightness of lighting sources. Similarly, with several interfaces present in the window, reflections have the potential to produce glare which could obscure the image. Staging and placement of lenses can reduce the glare with this challenge. Polarizing filters can also be used to reduce glare, at the expense of further reducing light transmitted to the camera and requiring additional lighting [22].

To be able to image through the thick window at HFEF to the load frame, which is several feet away from the inside of the window, a long working distance on the order of 10 feet between the specimen of interest and the lens is necessary. Combined with the small field of view required for testing (from a few inches to a quarter of an inch), this becomes challenging as there are few lenses that can satisfy the long working distance and high magnification requirements. At these conditions, the depth of field is generally reduced, limiting movements towards and away from the lens which can maintain appropriate focus. This becomes a challenge for stereo calibration, which requires manipulation of the calibration target through a range of rotations and translations. For effective through-window measurements, these challenges need to be considered and planned for.

2.3. Path to Implement Through-Window DIC

The path toward implementation of a through-window DIC method must answer the questions raised in the previous section. The first of these is the requirement to rigidly mount the camera and lens system on the outside of the window so that the calibration and test images can be taken. A simple solution would be tripod mounts for each camera, but due to the sensitivity of the calibration to small changes in camera position having a more robust method would be advantageous. Another practical consideration is that the cameras and facility operators will need to share the working space in front of the window during the testing campaign. It is therefore important that the immediate working area in front of the window remain clear to give room for the operators to work and decrease the likelihood that the camera setup could be disturbed during specimen loading. As was noted, longer working distance make the imaging more challenging, so bringing the setup as close to the windows as possible is preferable.

A preliminary design for such a camera frame was generated to accommodate these considerations, as shown in Figure 4. The frame is simple extruded aluminum t-slot framing that attaches directly to the shield window frame. This allows for the cameras to be as close as possible and keeps the floor space in front of the window clear for the operators. Additionally, the frame was attached utilizing twist-lock magnets. The desire was to have a non-permanent attachment to the window so that it could be removed between testing campaigns to free up the space for the operators but also lends itself to the frame being installed on other windows easily if there is another project that could benefit from DIC. It also limits any influence of the setup on the window, reducing the likelihood of requiring an EC process for impacting a safety significant system, although any changes would require thorough evaluation before implementation.

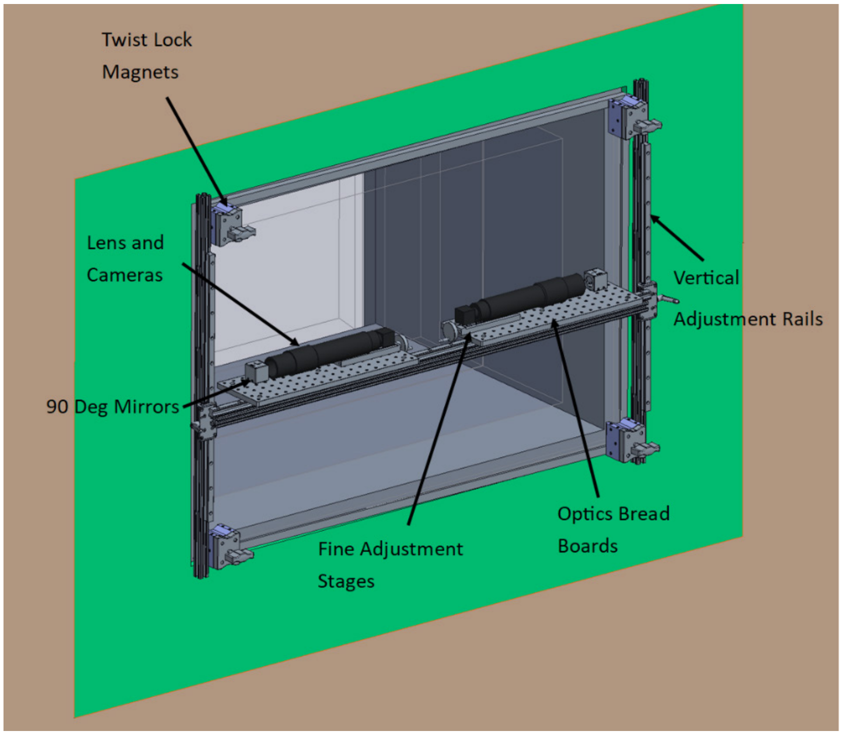


Figure 4. Schematic of the preliminary design of the camera and lens mounting system for through-window DIC.

This frame allows movement in two translational and one rotational (tilt) degrees of freedom.

The frame would allow positioning of the cameras within the plane of the window via linear bearings and rails. Optics bread boards would allow modular adjustment and adaptability for future changes. 90-degree mirrors would also be included so that the long lenses could be oriented along the window. This further improves the working area for the operators and decreases the distance the cameras protrude out from the window, allowing for better stability of the twist lock magnet system. Precision positioning stages both linearly and rotationally will allow for small precise adjustments when fine tuning the set up. It is also much simpler than an in-cell mounting system, as it can be completely operated by hand and no remote-operation modifications are needed. The camera frame setup being mainly purchased parts, and avoiding the EC process required of in-cell modifications, would make it relatively inexpensive with a short lead time.

The refraction challenge has perhaps the greatest potential to frustrate through-window DIC efforts. However, there are recent advancements in off-the-shelf commercial DIC software which show promise in overcoming the refraction distortions. Generally, stereo DIC calibration is used to determine parameters intrinsic to a single lens-camera pair such as image center, lens distortions, and focal length, as well as extrinsic parameters of the combined dual-camera system such as the relative position of the cameras to each other and to the specimen. However, using a more complicated model in the calibration such as a 4th or 5th order variable ray origin (VRO) scheme [23], [24] can account for refraction-induced distortions as well as lens and other distortions. This is particularly effective with the use of a hybrid calibration, in which a secondary calibration is performed with a speckled plate to provide many more data points for distortion parameter identification. This has been shown to be effective when imaging through thick windows and refractive fluid layers, even at sharp incident angles [17], [23]–[25]. Although the hot cell windows are likely thicker and multipaned than the applications cited above, the availability of off-the-shelf solutions to refraction make the through-window method appealing.

The associated issue of dispersion also has a very promising and simple potential solution. Because the phenomenon is wavelength-dependent, using an optical bandpass filter at the front of the lens would narrow the wavelengths of light transmitted to the camera sensor. This technique of targeting specific wavelengths has been previously used for high-temperature DIC applications to overcome blackbody radiation [26]–[28] and for high-magnification and long working distance DIC applications to overcome the diffraction limit of light [29]. Such bandpass filters are very inexpensive, off-the-shelf commercial components, making this a very quick solution. The narrower the band of transmitted wavelengths, the greater the clarity due to reduced dispersion. This must be balanced against the reduced amount of light transmitted, which means greater lighting is needed to prevent image dimming. However, this balance is easy to find as filters are available with several widths of transmitted range and several peak wavelengths.

The final challenge to consider is the long working distance and high magnification requirements. There are lenses capable of these specifications, and single-camera DIC has been demonstrated at similar working distances and magnifications previously [29]. Thus, the primary concern is if the depth of field in such conditions is sufficient for adequate stereo calibration. Preliminary tests with the long-distance lenses showed that calibration with a printed target and a freely available DIC software [30] was successful in air at a working distance of roughly 10 feet. It can reasonably be expected that the calibration with a commercial software and accompanying precision calibration target would yield equal or superior results. Importantly, the images showed good focus through a few inches of motion towards and away from the lens, sufficient for stereo calibration and in line with the previous work using this lens [29]. If additional depth of field is required, the aperture can be adjusted for the needed improvement.

After the in-air preliminary imaging, tests were also conducted to assess the potential of the VRO technique, as seen in Figure 5. Two large glass tanks which were filled with water and placed in the imaging path of the long-distance lenses. One tank was 14 inches thick, the other 17 inches thick, with glass wall thickness of 3/8 inch, and a 12-inch air gap was left between the two tanks. The lens tip was 9 inches from the closest tank wall, and the overall working distance from the lens to the specimen was 9 feet 8 inches. The result is imaging through a rudimentary mockup of a thick window. Although not an exact replica of the hot cell window, it is roughly the same thickness and consists of several different media with varying refractive indices, capable of providing a reasonable indication whether the refractive distortions can be overcome. An example calibration image can be seen in B) and E) of Figure 3. With the basic baseline case of the freely available DIC software, a successful calibration was performed when imaging through these tanks, although a better calibration score would be needed for quality measurements. The commercial DIC software was also able to calibrate with the standard radial camera model, but the calibration score was significantly improved when moving to the 5th order VRO camera model. A speckled surrogate specimen was also imaged as seen in C) and F) of Figure 3, and the DIC was able to track the specimen with minimal dropped subsets through a range of translations and bending strains.

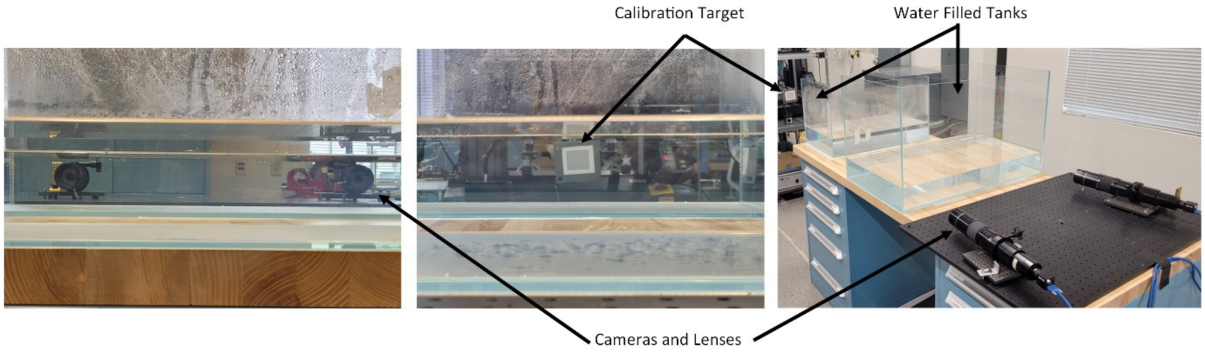


Figure 5. Mock-up setup for through-window DIC. View through the tanks to the cameras from the perspective of the specimen (left), view of the calibration target from the cameras (center), and view of overall positioning of the setup (right).

It should be noted that in these preliminary tests, no optical bandpass filter was used, and simple printed calibration targets were used. The dispersion effect is clearly visible in the blurring of E) and F) of Figure 3, and results are expected to greatly improve in noise and error reduction once the bandpass filter is included. Additionally, optimization of the speckle pattern size for the image application will improve results, as will the addition of a precision calibration target and the inclusion of a hybrid calibration step with a speckled plate. With promising preliminary results and several simple methods for improving result quality, there is a high chance of success in performing through-window DIC. The next steps for implementation are characterization tests of increasing rigor, first with mock windows followed by demonstration with the hot cell window. These tests would address the dispersion solution with the optical filter, the refraction with a VRO calibration including hybrid calibration, speckle optimization, and the use of the long-distance lenses for the magnification/depth of field concerns. A key piece would be the characterization of strain resolution and DIC result uncertainties. Successful demonstration in these tests, in parallel with the engineering process for the camera mounting system, would establish the through-window method as a viable system ready for implementation.

3. CAMERAS PLACED INSIDE THE CELL

The other primary option for enabling DIC deployment for irradiated cladding and materials at the HFEF main hot cell is to place the cameras and lenses inside the cell and circumvent the need to image through the window. This eliminates the refraction, dispersion, and long working distance challenges, but introduces new challenges of its own. Several of the advantages of this method match with the disadvantages of through-window DIC and vice versa. The sections below highlight these advantages and disadvantages, along with the potential path to implementation.

3.1. In-Cell Method Advantages

The obvious advantage to placing the optical equipment inside the main cell is avoidance of the challenges associated with through-window imaging. This means that there are not challenges with refraction distortions, dispersion-induced loss of clarity, or reflections and glare at window interfaces. Along with this, the lighting difficulties due to transmission losses through the window are alleviated, allowing more margin in other lighting control parameters such as aperture and exposure time.

Another advantage is the ability to design a more permanent setup. While the cameras and lenses still need a specially designed positioning system for in-cell mounting, there is the potential to make this system more permanent than the through-window method would allow. The benefit to this would be limited likelihood of accidentally bumping or moving the setup between the calibration phase and later image capturing. Reduced risk of bumping correlates to greater confidence in results and lower probability of increased operator and window time due to recalibration.

Perhaps chief among the advantages is the shorter working distance between the lens and the specimen of interest. This in turn reduces the magnification power needed from the lens, potentially expanding the number of lens options available. It also likely enables smaller fields of view without the potential compromise of imaging quality or depth of field. At a shorter working distance, it is much easier to have a large depth of field, improving stereo calibration and reducing measurement error for out-of-plane motions. This could enable a wider variety of tests to be paired with stereo DIC, and likely offers improved strain resolution due to the higher magnifications possible.

3.2. In-Cell Method Challenges

The main challenges that face an in-cell system are due to the harsh environment of in-cell. Electronics of any kind are particularly susceptible to the effects of high radiation fields and camera systems are no exception. Additionally, the radiation fields are also harmful to optics in the form of browning of the lenses which will affect the images captured. One of the primary associated issues is the uncertainty of when the degradation occurs. While optics failing between test campaigns would only require new equipment to be sent in-cell before the next campaign, failure during a campaign or during a test poses additional problems. For example, if the sensor degrades and dead pixels appear during a test, these will appear as dark pixels and will cause additional errors in the image correlation. Such errors being introduced during the middle of a test would not be captured in pre-test error and noise quantifications. These unaccounted-for errors could clearly be an issue for obtaining qualified data.

Radiation hardened cameras exist and have been implemented in-cell before but have not been utilized for precise measurement applications such as DIC. Their application has generally been for real-time visual inspection, at lower resolutions and magnifications relative to what is generally used or available for out-of-cell DIC. To use off-the-shelf radiation hardened cameras, concessions likely will need to be made in sensor resolution, magnification, and some controllability/tunability of physical settings. These challenges potentially negate some of the advantages of using in-cell cameras. To lengthen in-cell lifespan, the cameras may need to be further protected via some shielding specifically designed for the cameras. If non-radiation hardened cameras were used to gain the full advantage of in-cell positioning, an even greater degree of shielding should be implemented, and shorter lifespan of cameras and lenses can be expected. In addition to the shielding while cameras are in use, good practices can be implemented such as storage of the cameras in a further shielded container located away from any significant sources of radiation. However, this would remove the permanent location benefit outlined previously in the in-cell camera advantages section. Even with these precautionary steps put in place the lifetime of the camera would be in question and it is unclear the extent of degradation the camera could endure and remain adequate for DIC use.

Regardless of the projected lifespan, it is likely that the cameras and lenses will need to be considered as a consumable. This would require new optical equipment to be sent in-cell on an as-needed, currently undefined basis. However, this introduces some level of operational risk; testing campaigns may be forced to pause if the ability to send new optical equipment in-cell due to facility maintenance, unexpected transfer outages, or unexpected camera failure during a campaign. The forced change in camera could add uncertainty to the measurements and difficulty comparing specimens from the old setup to the new.

Another challenge is data transfer. As noted earlier, cameras typically used for DIC use USB or ethernet connections, sometimes, with an additional power supply and synchronization triggering cable. While electrical power is routinely transferred through the cell wall, these type of camera data transfers are not as common. This generally would require a custom modification to the specific feedthrough, which is an expensive and time-consuming task. It requires additional work through the EC process as feedthrough modification affects a safety significant system and requires radiological control support to have an opening to the cell. It is possible that the camera cabling could use the existing feedthrough by designing a new pin connector, but this will likely result in degradation of the signal due to no electrical shielding of the wiring, and could still require working through the EC process. A radiation-hardened camera would have a different cable, but would still need a similar modification of the feedthrough or cable connection.

The fine-tunability of the lens and camera system if placed in-cell also remains an important issue. DIC requires precise adjustment of camera positions in several degrees of freedom, in addition to focus, aperture, and other physical parameters. These generally need to be adjusted multiple times during the calibration phase. Fine position adjustments can be on the order of a few thousandths of an inch and include translations in at least two dimensions as well as rotational degrees of freedom. These small adjustments strongly affect the results. The lack of dexterity of the remote manipulators would mean that this process must be specially design to be remote operation ready, which is further complicated if camera shielding is also needed. The remote tuning and adjustment steps would be long and tedious, adding significant operator and window time as part of each campaign. This reduces facility throughput at the load frame and increases test campaign cost. Additionally, this process adds additional engineering cost as part of the EC process. Furthermore, switching from one lens to another would be an added challenge, likely precluding some level of flexibility for different test campaign setups. Some radiation-hardened camera and lens systems have motorized zoom, aperture, and focus functions, which would eliminate most of this burden. However, that motorized control is likely to complicate cell wall feedthroughs, and positioning and mounting in-cell would still be a requirement.

After the calibration phase, the camera setup must not be moved or bumped prior to or during testing, or the calibration would need to be performed again. However, loading and unloading of the specimens would need to be done around the camera setup, which would need to be directly in front of the test train. This adds increased complexity that may not be possible to achieve with the remote manipulators. It is likely that the in-cell mounting system will need to be removable to store the cameras in shielding when not in use, and to make room for non-DIC campaign operations at the window. This removes the potential advantage of a more permanent setup previously mentioned. The design is also more likely to be location-specific, meaning it would not be easily moved to a different setup at a different window, unlike the through-window mount which has the same window interface regardless of location.

3.3. Path to Implement In-Cell Cameras

Many of the challenges listed above require engineering solutions. The challenge of the damaging radiation fields has two potential solutions: using off-the-shelf radiation-hardened cameras and lenses or using traditional cameras and lenses with custom-designed shielding. The radiation hardened cameras have the advantage of reduced in-house customization and would be the first choice. However, concerns about resolution limitations, cell-wall feedthroughs, magnification, and data transmission would need to be addressed. This would likely involve purchase of radiation-hardened cameras and out-of-cell testing, as well as engineering effort for cabling and feedthroughs. The cameras have the potential for motorized control of zoom, focus, and aperture, but these controls would likely further complicate cell wall feedthrough issues and would need additional testing.

The second choice would be using traditional cameras and lenses with custom shielding. Similar feedthrough issues would exist, although using existing cabling and creating a custom cable adapter to use with an existing feedthrough is more likely for the traditional cameras than for motorized radiation-hardened software. However, it comes with additional challenges of increased noise and data loss. As with the radiation hardened solution, the path forward would include purchase of cameras and lenses and engineering effort with the feedthroughs. Unlike the radiation-hardened cameras, less out-of-cell testing would be needed, but after cabling and feedthrough engineering effort is completed comprehensive in-cell testing would be needed to determine the lifetime, reliability, and propagated errors in imaging and subsequent DIC measurement.

For both in-cell camera options, engineering effort would also be needed for the camera mounting and positioning system. This would have to lift the cameras above the working table surface to the same vertical position as the test train, and independently provide the degrees of freedom. As noted previously, this system must allow flexibility and rigidity as the through-window method does, but without the inherent rigidity of the window. Importantly, it must have a minimal physical footprint, so that calibration target movements, specimen loading and unloading, and other test train adjustments can be done around but without touching the mounting system. Additionally, it must be removable so that other equipment can be used in the same space after DIC campaigns. To implement this system, custom engineering solutions that meet these requirements must be designed and undergo the full EC and EQP process. If the traditional cameras and lenses with custom-designed shielding were used, additional EC and EQP effort must be expended to design and implement a system for remote manipulation through the shielding to adjust the focus, zoom, and aperture. For both in-cell camera options, input from and training of operators to use the designed equipment would be required as part of the EQP.

INL's EC process will guide the implementation of any developed equipment whether in-cell or out-of-cell. This process at a high level involves, identifying discipline interfaces to ensure that all aspects of the design and its interaction with the facility have been reviewed by individuals familiar with the different aspects of the modification. The system is then designed and documented via drawings and procedures. A final design review is performed to ensure that the final system is ready for fabrication and implementation. The developed drawings and other support documents are all reviewed and released on EDMS so that the configuration can be managed. Any equipment is fabricated. Checkout and testing is performed leading to implementation and turnover to the facility for use.

It is worth noting that for in-cell equipment a rigorous 3-phase EQP is followed in addition to the general EC process described above. The 3-phases include, first an equipment checkout to ensure the equipment was fabricated according to the drawings and correctly assembled. Second, it is verified that it functions as intended and can be operated remotely by testing at a mock-up remote manipulator wall and finally is sent in-cell for testing in its final configuration prior to doing any work on actual material.

For the in-cell camera system this process will need to be followed and adds significant time and expense to the project. With the out-of-cell system, this process can most likely be abbreviated or omitted due to no need to train operators or perform additional engineering to ensure remote operability. This can save months of time and reduce the need of engineering and operation support. It is anticipated that the need to perform the EQPs and ECs would cost an additional $350,000 as a best case if radiation-hardened cameras can be used, and likely another $300,000 if the additional engineering for custom shielding and lens parameter remote control is also needed. If the existing feedthroughs cannot be used for either system and a customized wall feedthrough needs to be installed, the cost of such an extensive facility change would be yet another cost element on the order of $500,000 and would thereby likely exclude in-cell cameras as a feasible DIC option. All these additional cost elements pose risk of escalating the implementation cost of in-cell DIC to well over $1M.

4. COMMON TASKS AND CHALLENGES

In addition to the challenges and proposed solutions discussed above which are unique to each method, there are some shared tasks which need to be addressed regardless of the method chosen. These generally apply to ancillary tasks related to DIC measurement, not to the specific imaging requirements. Each challenge is briefly described below along with proposed solutions.

4.1. Lighting

One of the key issues for both systems is providing sufficient lighting for the imaging. Regardless of the method chosen, a dedicated lighting system is standard practice and should be implemented. If the through-window imaging is pursued, it is likely that additional strength lighting will be needed to overcome filtering for dispersion and transmission losses through the window. In either case, it is possible to shine additional lighting through the window to avoid the need for any in-cell system, but the intensity would be reduced by transmission losses. In the case of through-window imaging, this would be relatively simple to attach to the same mounting platform as the lenses, without requiring any additional engineering process. Currently lighting used in-cell is primarily halogen lights. These lights are original to the design of the hot cell and were chosen at that time due to their longevity in high radiation fields. Light-emitting diode (LED) lighting is currently being developed for the hot cell facilities at INL's Materials and Fuels

Complex (MFC). The new LED lights are not expected to increase the brightness but primarily help with maintenance, power consumption and heat generation. With normal 120 volts alternating current (VAC) power readily available at all windows it would be feasible to use halogen or LED lighting sources in-cell placed near the specimen of interest during testing, using similar power supplies. This would likely need some positioning mechanism, although this requires much less fine control and detail than an in-cell camera positioning system.

In addition to the intensity of the light source, other image brightness controls also exist to assist in optimizing image collection: aperture, exposure time, and gain on the camera amplifier [31]. Wider apertures increase brightness and reduce the diffraction-caused blurring but reduce depth of field. Longer exposure times also increase brightness well for quasi-static testing but pose motion blurring challenges in a dynamic high-speed test setting. Gain is generally considered the worst option for counteracting shortfalls in lighting as it increases noise. Despite these inherent tradeoffs, a combination of these methods is often employed to optimize image brightness, and a similar balance can be used here as well. If the light source can be placed out-of-cell, the lighting challenge would be easier for the through-window method, but if it is placed in-cell it is likely easier for the in-cell method. Regardless, the light source task is not expected to be overly burdensome for either method.

4.2. Calibration

The calibration phase is a critical step for stereo DIC and must be addressed for a complete DIC setup. Accurate calibration requires taking images of a calibration target such as the one shown in D) and E) of Figure 3. This calibration images are taken with both cameras after they are placed in their final positions and all lens settings are finalized. The rigid calibration target is articulated through a range of translations and rotations within the field of view of both cameras, with a single image pair captured at each position. It is important that the calibration target is placed at the same spatial location as the specimen to be imaged during the test, which means it must be placed in the cell. It is also important that the target is motionless during imaging, which means it should not be actively held by a remote manipulator.

However, there are articulating stages commercially available, and only slight modifications are expected to be needed to make the control remote. The expected order of operations is to place the calibration target in the stage, gently move the remote manipulator to slightly reposition the target, capture the image pair, and then repeat the target repositioning and image capturing steps. The challenge for the in-cell system would be to perform the calibration and repositioning with the remote manipulators without touching the camera setup. If high magnification setups are achieved with a field of view of less than one inch, it is likely that a glass backlit calibration target would need to be used. The fragility of the glass target and the backlight ability would complicate the setup, potentially removing some of the advantage of the higher magnifications that may be achievable with an in-cell camera setup. It is not expected that an EC process would be needed for this task. As both lighting and calibration setups will be primarily off-the-shelf parts with minor modifications, the expected upfront cost together is on the order of $50,000.

4.3. Speckle Pattern Application

An important preparatory task for any DIC imaging, whether single camera or stereo, is the sample patterning. A high-contrast low-noise speckle pattern is needed so the DIC algorithm can track pixel subsets of the sample surface through the deformed images [32]. This can be produced by a variety of methods, such as rubber stamp sets, spray paint, paint stencils, printed patterns, and more. In some cases, even the natural texture or surface roughness of the material provides sufficient contrast for imaging, although these tend to be restricted to microscale measurements [33]. For the intended applications in-cell, patterns need to be applied to a specimen of interest after irradiation. This will likely take the form of a black or white speckle applied to a white or black background, respectively. If needed, this can be applied directly to the specimen surface.

For repeatability and consistent application of the speckle pattern, a stamp or stencil is the most likely option for implementation in-cell. A single stamp could be used for a certain field of view, ensuring the speckle size is optimized for the image size and resolution. A black or white paint, dye, or similar component could easily be used with the stamp pad, and simple fixturing to hold the stamp and/or sample in place would be sufficient to apply the speckle. This would be relatively simple to implement a stamping method in the HFEF containment box, a window where sample preparation generally occurs, and is not expected to require any significant engineering effort.

4.4. Need for Commercial License

Rather than using a freely available DIC software, both methods would benefit from investment in a commercial stereo DIC software license. In collecting data from mechanical tests on irradiated cladding and other materials, understanding the uncertainty of reported measurements is critical. Commercial software is capable of providing this information, and through significant investment of time and money these commercial algorithms are more likely to provide robust measurements with reduced errors. Additionally, the offering of modules like VRO comes at no additional cost, enabling specialized applications. There is no INL engineering associated with this, just the license cost which would be identical for both through-window and in-cell camera methods.

5. ALTERNATIVE OPTIONS

In addition to the methods discussed in detail above, other options were also considered for their potential to enable DIC measurements of in-cell tests. However, they come with significant hurdles and barriers which make them less tenable at the present. Nevertheless, they are briefly mentioned and discussed here for thoroughness.

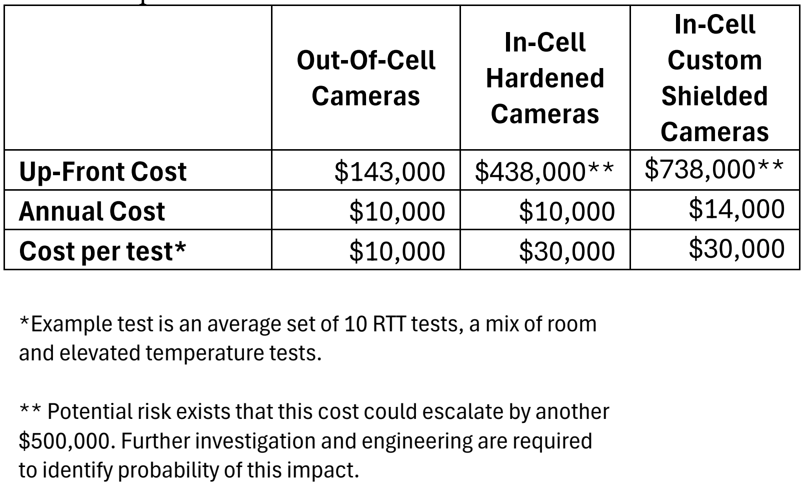
One option is to utilize an existing penetration through the hot cell wall and repurpose as a periscope feedthrough. Similar periscopes exist at different locations in HFEF and have been used for visual inspection with a camera or for manual inspection of parts. However, the primary challenge here is that a periscope is not currently installed at the window where the load frame is located, and the time and effort for installing one is prohibitively expensive. If one were installed, the periscope penetration in the wall would not be lined up with the specimen testing area in the load frame, requiring additional equipment with a series of mirrors to be designed and installed to redirect the viewing axis. Finally, this would only accommodate a single camera direction, and two cameras separated by a stereo angle are needed for the stereo DIC desired.

Another option is diffraction-assisted digital image correlation. This uses a transmission diffraction grating placed between the specimen and the camera to perform stereo DIC with the use of a single camera. The use of the diffraction grating produces a series of images from different perspectives, with two first order diffraction images simulating stereo viewing angles in addition to a typical zeroth order transmitted image [34], [35]. While this has worked for performing stereo DIC with a single camera, there are some important limitations. There is a significant reduction in available resolution, as three images would be transmitted onto the field of view of a single camera. This also is inversely related to the available stereo angle, as it generally provides narrow stereo angles. For a wider stereo angle, a wider field of view is needed, further reducing the resolution. The results are also very sensitive to the positioning of the diffraction grating, as greater distance between the grating and the specimen requires a larger grating, which means a larger field of view and worse resolution. Presumably this would be used with a single through-window camera to avoid sharp incident angles that are accompanied by refraction and dispersion challenges. However, a larger field of view also correlates with a wider viewing angle, which will begin to add to refraction and dispersion errors at the periphery of the field of view. In effect, it may add as many or more problems as it solves, and it requires precise placement of objects both on the outside of the window and inside the cell.

6. COST CONSIDERATIONS

Table 1 below shows a rough estimate of the cost associated with implementing either of the main alternatives. The implementation of the out-of-cell camera solution is much lower cost when compared to the in-cell camera solution. The low cost of implementation makes this alternative a very good candidate for the first foray into DIC in HFEF, as it will allow the team to determine viability early and at low cost, when compared to the in-cell solutions.

Table 1: Alternative Cost Comparison



	Out-Of-Cell Cameras	**In-Cell Hardened Cameras**	**In-Cell Custom Shielded Cameras**
Up-Front Cost	$143,000	$438,000**	$738,000**
Annual Cost	$10,000	$10,000	$14,000
Cost per test*	$10,000	$30,000	$30,000

*Example test is an average set of 10 RTT tests, a mix of room and elevated temperature tests.

** Potential risk exists that this cost could escalate by another $500,000. Further investigation and engineering are required to identify probability of this impact.

7. FINAL RECOMMENDATIONS

In considering the two primary methods of enabling DIC at the HFEF hot cell, both have plausible paths forward. Both would require some level of additional work, design, and testing before being ready to deploy. The through-window method has less engineering work and associated EC or EQP process burden, which will result in lower cost and overall effort, and shorter lead time to implementation. It also will take less work during a campaign with faster calibration and setup times, requiring fewer operator resources and increasing throughput. The key challenge is demonstrating the available tools and methods, including the VRO method for overcoming refraction and the use of optical filters to overcome dispersion. This can be accomplished with out-of-cell testing and off-the-shelf commercial software solutions. As such, the through-window method is the preferred method for implementing DIC at HFEF, and the authors recommend that the testing and development efforts outlined in this report should be undertaken.

Conversely, the in-cell camera method likely requires less benchtop demonstration work to benchmark performance but will take additional effort for in-cell engineering work. This will include lengthy and involved engineering change and equipment qualification procedure processes, and so this method carries higher associated costs and greater risk of further cost increases and time delays. Thus, this in-cell camera method should be considered as a secondary option, if efforts for the through-window method prove unsuccessful. For the in-cell camera method, the radiation-hardened commercial camera and lens option should be the preferred camera because of its incorporated shielding for extended lifetime and its motorized optical parameter controls. However, there may be additional barriers with feedthroughs and resolution limitations. If further engineering cannot resolve those issues, then traditional camera and lens pairs should be used, with the additional custom shielding and remotely operable optical controls.

Pursuing through-window DIC imaging as the primary choice, with in-cell radiation-hardened cameras and custom-shielded traditional cameras as secondary options, provides the best path for success. The addition of this full-field strain measurement capability provides significant opportunities for improved outcomes in mechanical testing of irradiated cladding and other materials at the HFEF hot cell.

8. REFERENCES

[1] M. A. Sutton, J. J. Orteu, and H. Schreier, *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts,Theory and Applications*. Springer Science & Business Media, 2009.

[2] P. Bing, X. Hui-min, H. Tao, and A. Asundi, “Measurement of coefficient of thermal expansion of films using digital image correlation method,” *Polymer Testing*, vol. 28, no. 1, pp. 75–83, Feb. 2009, doi: 10.1016/j.polymertesting.2008.11.004.

[3] S. M. Guo, M. A. Sutton, N. Li, X. D. Li, L. W. Wang, and S. Rajan, “Measurement of Local Thermal Deformations in Heterogeneous Microstructures via SEM Imaging with Digital Image Correlation,” *Exp Mech*, vol. 57, no. 1, pp. 41–56, Jan. 2017, doi: 10.1007/s11340-016-0206-6.

[4] G. L. Golewski, “Comparative measurements of fracture toughgness combined with visual analysis of cracks propagation using the DIC technique of concretes based on cement matrix with a highly diversified composition,” *Theoretical and Applied Fracture Mechanics*, vol. 121, p. 103553, Oct. 2022, doi: 10.1016/j.tafmec.2022.103553.

[5] S. Karnati, Y. Zhang, F. F. Liou, and J. W. Newkirk, “On the Feasibility of Tailoring Copper–Nickel Functionally Graded Materials Fabricated through Laser Metal Deposition,” *Metals*, vol. 9, no. 3, Art. no. 3, Mar. 2019, doi: 10.3390/met9030287.

[6] P. Lava, E. M. C. Jones, L. Wittevrongel, and F. Pierron, “Validation of finite-element models using full-field experimental data: Levelling finite-element analysis data through a digital image correlation engine,” *Strain*, vol. 56, no. 4, p. e12350, 2020, doi: 10.1111/str.12350.

[7] S. K. Lee *et al.*, “BISON validation of FeCrAl cladding mechanical failure during simulated reactivity-initiated accident conditions,” *Journal of Nuclear Materials*, vol. 564, p. 153676, Jun. 2022, doi: 10.1016/j.jnucmat.2022.153676.

[8] P. M. Beck *et al.*, “Mandrel diameter effect on ring-pull testing of nuclear fuel cladding,” *Journal of Nuclear Materials*, vol. 596, p. 155087, Aug. 2024, doi: 10.1016/j.jnucmat.2024.155087.

[9] R. Hansen, “High-Magnification Digital Image Correlation Techniques for Aged Nuclear Fuel Cladding Testing,” All Graduate Theses and Dissertations, Utah State University, Logan, Utah, 2021. [Online]. Available: https://digitalcommons.usu.edu/etd/8234

[10] A. Syed, M. K. Samal, J. Chattopadhyay, and P. Dutta, “Fracture toughness evaluation of axially-cracked tubular thin-walled specimens of Zircaloy-4 and its implications for integrity analysis of nuclear fuel clad,” *Theoretical and Applied Fracture Mechanics*, vol. 106, p. 102449, Apr. 2020, doi: 10.1016/j.tafmec.2019.102449.

[11] D. Kamerman *et al.*, “Development of axial and ring hoop tension testing methods for nuclear fuel cladding tubes,” *Nuclear Materials and Energy*, vol. 31, p. 101175, Jun. 2022, doi: 10.1016/j.nme.2022.101175.

[12] D. Kamerman, “The deformation and burst behavior of Zircaloy-4 cladding tubes with hydride rim features subject to internal pressure loads,” *Engineering Failure Analysis*, vol. 153, p. 107547, Nov. 2023, doi: 10.1016/j.engfailanal.2023.107547.

[13] K. Kane, N. Capps, B. Garrison, B. Johnston, S. Bell, and K. Linton, “Development and Implementation of Digital Image Correlation for Out-of-Cell Burst Testing,” Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2021.

[14] R. S. Hansen, D. W. Kamerman, P. G. Petersen, and F. Cappia, “Mechanics of the Ring Tension Test (RTT): A Finite Element-based Investigation,” Idaho National Laboratory, Idaho Falls, ID, INL/RPT-22-68606, Sep. 2022.

[15] M. N. Cinbiz, T. Koyanagi, G. Singh, Y. Katoh, K. A. Terrani, and N. R. Brown, “Failure behavior of SiC/SiC composite tubes under strain rates similar to the pellet-cladding mechanical interaction phase of reactivity-initiated accidents,” *Journal of Nuclear Materials*, vol. 514, pp. 66–73, Feb. 2019, doi: 10.1016/j.jnucmat.2018.11.023.

[16] M. Le Saux, J. Besson, and S. Carassou, “A model to describe the mechanical behavior and the ductile failure of hydrided Zircaloy-4 fuel claddings between 25 °C and 480 °C,” *Journal of Nuclear Materials*, vol. 466, pp. 43–55, Nov. 2015, doi: 10.1016/j.jnucmat.2015.07.026.

[17] B. A. Lane, R. J. Cardoza, S. M. Lessner, N. R. Vyavahare, M. A. Sutton, and J. F. Eberth, “Full-field strain mapping of healthy and pathological mouse aortas using stereo digital image correlation,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 141, p. 105745, May 2023, doi: 10.1016/j.jmbbm.2023.105745.

[18] T. Allanche *et al.*, “Radiation vulnerability of standard and radiation-hardened optical glasses at MGy dose: Towards the design of tolerant optical systems,” *Journal of Non-Crystalline Solids*, vol. 585, p. 121531, Jun. 2022, doi: 10.1016/j.jnoncrysol.2022.121531.

[19] E. M. C. Jones and M. A. Iadicola, “A Good Practices Guide for Digital Image Correlation,” International Digital Image Correlation Society, Oct. 2018. [Online]. Available: https://www.idics.org/guide/DICGoodPracticesGuide_ElectronicVersion-V5g-181022.pdf

[20] C. W. Solbrig and S. A. Warmann, “Thermal Stress in HFEF Hot Cell Windows Due to an In-Cell Metal Fire,” *World Journal of Nuclear Science and Technology*, vol. 6, no. 1, Art. no. 1, Jan. 2016, doi: 10.4236/wjnst.2016.61003.

[21] D. Swank, “AGC-1 Post Irradiation Examination Status,” IDaho National Laboratory, Idaho Falls, ID, Technical Report INL/EXT-11-23165, Sep. 2011. [Online]. Available: https://doi.org/10.2172/1031676

[22] W. S. LePage, S. H. Daly, and J. A. Shaw, “Cross Polarization for Improved Digital Image Correlation,” *Exp Mech*, vol. 56, no. 6, pp. 969–985, Jul. 2016, doi: 10.1007/s11340-016-0129-2.

[23] K. P. Lynch, E. M. C. Jones, and J. L. Wagner, “High-Precision Digital Image Correlation for Investigation of Fluid-Structure Interactions in a Shock Tube,” *Exp Mech*, vol. 60, no. 8, pp. 1119–1133, Oct. 2020, doi: 10.1007/s11340-020-00610-8.

[24] B. A. Lane, S. M. Lessner, N. R. Vyavahare, M. A. Sutton, and J. F. Eberth, “Null strain analysis of submerged aneurysm analogues using a novel 3D stereomicroscopy device,” *Computer Methods in Biomechanics and Biomedical Engineering*, Jun. 2020, Accessed: Sep. 12, 2024. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/10255842.2020.1724974

[25] M. Yang, D. Xiang, S. Wang, and W. Liu, “The Radial Bulging and Axial Strains of Intervertebral Discs during Creep Obtained with the 3D-DIC System,” *Biomolecules*, vol. 12, no. 8, Art. no. 8, Aug. 2022, doi: 10.3390/biom12081097.

[26] R. S. Hansen, T. J. Bird, R. Voie, K. Z. Burn, and R. B. Berke, “A high magnification UV lens for high temperature optical strain measurements,” *Review of Scientific Instruments*, vol. 90, no. 4, p. 045117, Apr. 2019, doi: 10.1063/1.5081899.

[27] P. Dewanjee *et al.*, “Digital Image Correlation at Extreme Temperatures Using Shortwave Ultraviolet (UV-C) Lights and Filters,” *Exp Mech*, vol. 64, no. 4, pp. 551–563, Apr. 2024, doi: 10.1007/s11340-024-01044-2.

[28] R. B. Berke and J. Lambros, “Ultraviolet digital image correlation (UV-DIC) for high temperature applications,” *Review of Scientific Instruments*, vol. 85, no. 4, p. 045121, Apr. 2014, doi: 10.1063/1.4871991.

[29] R. S. Hansen, K. Z. Burn, C. M. Rigby, E. K. Ashby, E. K. Nickerson, and R. B. Berke, “Digital image correlation at long working distances: The influence of diffraction limits,” *Measurement*, p. 110493, Nov. 2021, doi: 10.1016/j.measurement.2021.110493.

[30] D. Z. Turner, “Digital image correlation engine (DICe) reference manual,” *Sandia report, Sand2015-10606 O*, 2015.

[31] T. Q. Thai, R. S. Hansen, A. J. Smith, J. Lambros, and R. B. Berke, “Importance of Exposure Time on DIC Measurement Uncertainty at Extreme Temperatures,” *Exp Tech*, vol. 43, no. 3, pp. 261–271, Jun. 2019, doi: 10.1007/s40799-019-00313-3.

[32] P. Reu, “Speckles and their relationship to the digital camera,” *Exp Tech*, vol. 38, no. 4, pp. 1–2, Jul. 2014, doi: 10.1111/ext.12105.

[33] Y. L. Dong and B. Pan, “A Review of Speckle Pattern Fabrication and Assessment for Digital Image Correlation,” *Exp Mech*, vol. 57, no. 8, pp. 1161–1181, Oct. 2017, doi: 10.1007/s11340-017-0283-1.

[34] S. Xia, A. Gdoutou, and G. Ravichandran, “Diffraction Assisted Image Correlation: A Novel Method for Measuring Three-Dimensional Deformation using Two-Dimensional Digital Image Correlation,” *Exp Mech*, vol. 53, no. 5, pp. 755–765, Jun. 2013, doi: 10.1007/s11340-012-9687-0.

[35] E. K. Nickerson and R. B. Berke, “Ultraviolet Diffraction Assisted Image Correlation (UV-DAIC) for Single-Camera 3D Strain Measurement at Extreme Temperatures,” *Exp Mech*, vol. 58, no. 6, pp. 885–892, Jul. 2018, doi: 10.1007/s11340-018-0394-3.