Title:

A Scaled Experimental Study of Control Blade Insertion Dynamics in Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactors

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Abstract:

Direct control element insertion into a pebble-bed reactor core is proposed as a viable control system in molten-salt-cooled pebble-bed reactors. Unlike helium-cooled pebble-bed reactors, this reactor type uses spherical fuel elements with near-neutral buoyancy in the molten-salt coolant, thus reducing contact forces on the fuel elements.

This study uses the X-ray Pebble Bed Recirculation Experiment facility to measure the force required to insert a control element directly into a scaled pebble-bed. The required control element insertion force, and therefore the contact force on fuel elements, is measured to be well below recommended limits. Additionally, x-ray tomography is used to observe how the direct insertion of a control element physically displaces spherical fuel elements. The tomography results further support the viability of direct control element insertion into molten-salt-cooled pebble-bed reactor cores.

Keywords:

- Granular dynamics
- Molten fluoride salt cooled reactor
- Control element insertion
- Pebble bed reactor
- Spherical fuel element
- X-ray tomography

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Acronyms

CoBIE – Control Blade Insertion Experiment
DAQ – Data Acquisition Device
DEM – Discrete Element Method
FHR – Fluoride Salt-Cooled High-Temperature Reactor
HTR – High Temperature Reactor
HTGR – High Temperature Gas Reactor
PB-FHR – Pebble-Bed Fluoride Salt-Cooled, High-Temperature Reactor
THTR – Thorium High Temperature Reactor
X-PETS – X-Ray Pebble Tomography Software
X-PREX – X-Ray Pebble Recirculation Experiment

1 Introduction

The control of reactivity in pebble-bed reactors is generally achieved by inserting control elements into channels in the graphite reflectors that confine the pebble-bed. Conversely, elements inserted directly into the pebble-bed can have very high reactivity worth, but have the risk of damaging or breaking pebble fuel elements. In 2012, U.C. Berkeley developed designs for control blades (Chang et al., 2012) that can be inserted directly into the pebble-bed of the Mark-1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (Mk1 PB-FHR) design (Andreades et al., 2014). The significant additional reactivity worth of these shutdown elements (compared to the control rods inserted into channels in the center graphite reflector) make them an attractive option for redundant and diverse shut down capabilities. The central reflector control rods, as well as the control blades studied here (also called shutdown blades, which would be inserted directly into the pebble-bed), are shown in Figure 1.

The force imparted to pebbles by a control blade inserted directly into a packed bed is a very important parameter to determine the viability of this type of shutdown system. The strategy of inserting control rods directly into a pebble-bed core was adopted for the gas-cooled pebble-bed Thorium High Temperature Reactor (THTR) in Germany (as seen in Figure 2). In this particular gas-cooled design, the forces imparted to pebbles led to a large number of broken pebbles, and complicated the initial operation of the facility (Rubin, 2001). In the salt-cooled pebble-bed reactor designs, the spherical fuel elements have positive buoyancy and float against the upper reflector of the core. In this case, the insertion of a control blade from the top of the bed may prove to be more feasible due to the reduced body forces in the positively buoyant system and the lubricity provided by the coolant. In the case of core designs with an unconstrained free surface at the bottom of the bed, there are additional degrees of freedom for pebble motion that would further reduce the forces imparted to pebbles and the potential for damage.

Figure 1. Mk1 PB-FHR core internals render (Andreades, 2014).

Figure 2. THTR pebble-bed core (6 cm pebbles) with control elements inserted (Cleve, 2013).

The X-ray Pebble Recirculation Experiment (X-PREX) facility at U.C. Berkeley is uniquely suited to study this safety-related design feature with capabilities for measuring blade insertion forces as well as tracking the positions of individual pebbles as the control blade displaces them. These results can additionally be used to validate Discrete Element Method (DEM) simulations, which can compute the forces on individual pebbles.

The Control Blade Insertion Experiment (CoBIE) was designed to examine the feasibility of blade insertion directly into a packed pebble-bed. The experiment measures the insertion forces required to drive a control blade directly into a packed pebble-bed, as well as the individual pebble displacements due to such an insertion. These experimental results are helpful for control blade and fuel element design for the use of control blade elements that insert directly into pebble-bed cores.

2 Experimental Setup and Methodology

The Mk1 PB-FHR core design consists of spherical graphite fuel elements cooled by a lithium and beryllium fluoride molten salt commonly referred to as “flibe” (Li_2BeF_4). The pebble fuel elements will float upwards due to their positive buoyancy in molten flibe. The control blades studied here would be inserted from the top of the core directly into the pebble-bed (in the direction of gravity), acting against the pebble buoyant force. To significantly simplify its design and operation, CoBIE is a dry experiment with control blades being inserted upwards into a pebble-bed, against gravity. Spherical fuel elements are represented in CoBIE by plastic spheres.

The X-PREX facility is uniquely suited for the operation of CoBIE (Laufer and Buster, 2015). The data acquisition (DAQ) system and the linear actuator control system provide the capability to drive the control blade insertion with precision linear motion, while gathering insertion force measurements. Additionally, the X-Ray Pebble Tomography Software (X-PETS), which was developed at U.C. Berkeley specifically to process data collected by the X-PREX facility, provides the novel capability of tracking individual pebble locations and rotations during a control blade insertion.

2.1 CoBIE Physical Description

CoBIE utilizes an acrylic test silo that can be combined with modular wedge inserts, a variety of control blade designs, and a packed pebble-bed of variable height (Figure 3). During an experiment, a polycarbonate control blade is driven upwards into a packed pebble-bed by a linear actuator. The force required for insertion is measured by three Tekscan FlexiForce A401 piezoresistive force sensors. Insertion force data is collected by a National Instruments DAQ-6009.

The pebbles used for this experiment are 1.25 cm in diameter (approximately 0.5 inches) and are made of high-density polyethylene. These pebbles are approximately 40% scale by length from the Mk1 PB-FHR design, which uses 3.0-cm diameter fuel pebbles. Additional 1.257cm polypropylene pebbles instrumented with a 0.33 mm diameter tungsten wire through the center are used to enable imaging with x-ray tomography.

Before any experiment begins, pebbles are poured into the test silo from the top opening to establish a random packing distribution. The pebbles are static during the duration of the test, and are not allowed to flow as they would in the Mk1 PB-FHR design. In a slowly draining pebble-bed, the packing structure exhibits spatial variation, as shown by Rycroft, C. H. et al. (2006). This could affect the insertion force of the control blade as it travels through regions of variable packing densities. This is a noted distortion in the experimental setup that has not been assessed at the time of this report.

Figure 3. CoBIE test silo physical arrangement without a packed pebble-bed showing the acrylic test silo mounted on the X-PREX assembly with linear actuator retracted and x-ray detector in-view.

The CoBIE test silo is fit with a modular pebble interface plane that is inclined at 45 degrees to the horizon (referred to as the “45-degree wedge”). The 45-degree wedge represents the central reflector interface in an annular PB-FHR core. The wedge contains a Teflon sleeve that acts as a low-friction stabilizing channel for the control blade insertion path.

The primary control blade design consists of a flat blade with stiffening ribs, creating a cruciform cross section (Figure 4). The thickness of the flat blade without stiffening ribs is equal to half of a pebble diameter (40% length scale in CoBIE). In the CoBIE system, the scaled cruciform blade is designed such that it can be fabricated out of 0.635 cm (0.25 in) polycarbonate sheets. The blades are designed to optimize pebble flow around the blades, which will be the case if defueling is performed with the blades inserted. The pebbles will flow around the blade without trapping, due to the blade’s narrow cross-sectional area. Additionally, the blades are hypothesized to minimize

pebble displacement during a control blade insertion event. The initial blade design was proposed by Chang et al. (2012) and was shown to be a viable design based on initial tests.

Figure 4. Primary CoBIE-scale control blade design. Top: cruciform cross section (dimensions in centimeters). Bottom: Blade compared to the 1.257 cm diameter pebbles.

The two main blade-geometry designs studied consist of a tip with two variable angles, and a tip with three variable angles, as shown in Figure 5. The naming convention may not be intuitive, so it is important to note that the blade tip with two variable angles has a third angle that is constrained at 90-degrees. It is also important to note that the designated angle of a blade tip is measured from the horizontal level, such that a 30° blade is blunt compared to a 60° blade. Figure 5 shows the naming convention and tip geometries for 30° two-angle and three-angle blades.

Figure 5. Blade geometries with annotations showing the defining angles in the tip. Left: 30-degree two-angle blade. Middle: 30-degree three-angle blade. Right: 5-angle blade tip.

One additional novel blade geometry tip was tested. The original theory was that the sharpest blade would require the least amount of force to insert into a packed pebble-bed. However, a blade with too sharp of a tip would not have sufficient structural integrity. Therefore, a modified blade tip was designed with five tip angles to yield a sharp tip, with a blunt base to provide adequate structural support. This blade can be seen on the right in Figure 5, and will be referred to as the 5-angle blade. Blades with sharp, right-angled edges, as well as fully rounded (referred to as full-bullnose) edges were both tested. The control blade insertion length varies slightly from blade-to-blade due to

variable tip geometry. The blade insertion length ranges from approximately 20 to 23 pebble diameters.

2.2 Notes on CoBIE Scaling

CoBIE was designed with consideration for how pebble contact forces and blade insertion forces will scale to a real reactor system. The length scale of CoBIE is approximately 40% of the Mk1 PB-FHR design, yielding a convenient laboratory scale (Table 1). Length dimensions are nondimensionalized using the pebble diameter d to yield position coordinates that can easily be applied to a reactor system. Notation in this report is to represent the Cartesian coordinate system as x/d , y/d or z/d , signifying the length along a given axis, divided by one pebble diameter. The z -axis origin ($z/d=0$) is defined as the location where the leading edge (or point) of the blade first contacts the pebble-bed. The x and y -axis origins ($x/d=0$, $y/d=0$) are defined at the center of the blade cruciform.

Table 1. Mk1 PB-FHR fuel pebble specifications (Andreades et al., 2014) and CoBIE/X-PREX pebble specifications (Laufer and Buster, 2015).

	Mk1 PB-FHR	X-PREX Unmodified	X-PREX Instrumented
Pebble Material	Graphite with TRISO	Polyethylene	Polypropylene
Plastic Density [kg/m ³]	-	960	900
Pebble Diameter [m]	0.030	0.0125	0.0125
Pin Material (For X-Ray Imaging)	-	-	Tungsten
Metal Density [kg/m ³]	-	-	19250
Pin Diameter [cm]	-	-	0.033
Effective Pebble Density [kg/m ³]	1745	960	960
X-Ray Image Width [Pixels]	-	-	3

CoBIE forces are nondimensionalized by a single pebble body force. These units, represented typically as F/mg , can easily be applied to a reactor with buoyant pebble fuel where mg is the body force on a single pebble (buoyant force minus gravitational force for the PB-FHR). The granular drag phenomena observed in a media pebble-bed cannot be described by a classical continuum scaling methodology, so a simplistic scaling methodology is employed. This approach is described as follows.

It becomes necessary to consider exactly how the motion of a blade inserted into a packed pebble-bed is resisted. Granular jamming effects have previously been studied as an effect of inhomogeneous stress propagation through stress chains of strained grains (Albert, I. et al., 2000). Overcoming such jamming effects requires the large-scale reorganization of the granular bed (Albert, I. et al., 2000). In an analogous manner, an object (a control blade, in this experiment) moving through a packed pebble-bed can only persist by inducing the same large-scale granular reorganizations (Albert, I. et al., 2001). Objects being dragged through a granular bed must reorganize the granular bed structure through creation and subsequent destruction of stress-chains in the granular media. The Coulombic friction model in cohesion with hydrostatic bed pressure have been used to describe the creation and propagation of stress chains in granular media

(Behringer et al., 1999, Cates et al., 1999). Both models are the direct result of pebble body forces, as well as pebble surface characteristics.

Accordingly, Albert, R. et al. (1999) shows that the force on an object being dragged through a granular bed is a linear function of the individual pebble body force. Albert, R. et al. (1999) further demonstrates that the critical force for an object to reorganize a granular bed (and therefore the granular drag and blade insertion forces) is directly proportional to the body force acting on a single grain (or pebble).

The pebble body force scaling factor is therefore used to linearly scale the blade insertion forces measured by CoBIE to an actual reactor system. CoBIE results are nondimensionalized by a single CoBIE pebble body force, and then (in Section 4.1) multiplied by the Mk1 PB-FHR pebble body force to yield dimensional results. The Mk1 PB-FHR pebble body force is calculated for a 3.0 cm diameter pebble buoyant in 650°C molten flibe. Pebble density is taken from Table 1, and flibe density is calculated using the density-temperature relation published by Williams et al. (2006).

The resulting body force and insertion force scaling factor is calculated to be:

$$\frac{F_{PB-FHR}}{F_{CoBIE}} = \frac{0.0302N}{0.0098N} = 3.08$$

Albert, R. et al. (1999) experimentally shows that the drag force is also proportional to the surface characteristics of individual pebbles. For this analysis, the surface characteristics are assumed constant between the CoBIE results and the actual reactor system. The accuracy of this approximation is discussed in relation to the CoBIE results in Section 4.2.

Table 2 summarizes the scaling parameters used in this report, as well as some of the scaling parameters that could be used to relate the results in this report to different pebble-bed reactor systems. High Temperature Gas-Cooled Reactor (HTGR) pebble properties are taken from the HTR-10 program in China (Tang et al., 2008). The 6.0-cm pebble in molten salt coolant is relevant for the Shanghai Institute of Applied Physics (SINAP) Thorium Molten-Salt Reactor Solid Fuel (TMSR-SF) program. The SINAP TMSR-SF pebble properties are assumed to be similar to the HTR-10 pebbles, with molten salt coolant properties assumed to be similar to flibe at 650°C.

Table 2. Summary of scaling parameters.

	CoBIE	Mk1 PB-FHR	SINAP TMSR-SF	HTR-10
Pebble Diameter (m)	0.0125	0.030	0.060	0.060
Pebble Density (kg/m ³)	960	1745	1760	1760
Coolant Density (kg/m ³)	Negligible	1962.8	1962.8	Negligible
Single Pebble Body Force (N)	0.0098	0.0302	0.2414	1.9507
Force Scaling Factor (Reactor/CoBIE)	1	3.08	24.63	199.05

2.3 Maximum Insertion Force and Uncertainty Analysis

In a randomly packed pebble-bed, the resistance to an object's motion is stochastic in nature, exhibiting large fluctuations, as shown by Albert, et al. (2000). Of particular concern for this study is the maximum force required to insert a control blade into a pebble-bed. The maximum force dictates both the functional specifications of the safety system, as well as the mechanical requirements of the fuel.

The methodology employed in this experiment selects five peak forces in a given insertion force profile, with the average and standard deviation of this subset yielding the maximum force with uncertainty. For this experiment, the five peak forces are selected manually by the author. While this method is somewhat subjective, it ensures that a maximum insertion force with uncertainty accurately represents a given data set. If the data set were larger, an automated statistical approach may be required.

A typical insertion force profile with the maximum insertion forces according to this methodology can be seen in Figure 6. The calculated average maximum force and the corresponding uncertainty can be seen to be a good representation for the maximum required insertion force for this experiment. In this study, uncertainty values are always calculated to include sensor uncertainty. Figure 7 shows the results of this methodology for five identical experiments. The repeatability of this maximum insertion force methodology verifies that it is an appropriate method for this study.

Figure 6. Typical insertion force profile with average maximum force and uncertainty calculated from five peak forces. Sensor uncertainty is included in the standard deviations. Tests performed with the 45-degree wedge, pebble-bed height of $48d$, and the 45-degree two-angle full-bullnose blade.

Figure 7. Maximum force for five identical experiments. Insertion velocities= 0.803 ± 0.014 d/s. All tests performed with the 45-degree wedge, pebble-bed height of $48d$, and the 45-degree two-angle full-bullnose blade.

3 CoBIE Experimental Results

3.1 Blade Insertion Hysteresis and Resistance Modes to Blade Insertion

An interesting phenomenon observed by CoBIE is the insertion force profile hysteresis. There is a dramatic difference between the shape of the insertion force profile for a blade inserted into a randomly packed bed, and the insertion force profile of the same blade during a subsequent insertion without any intermediate mixing or reordering of the pebble-bed.

3.1.1 Insertion Force Hysteresis

Control blade insertion hysteresis was observed by inserting the 45-degree two-angle no-bullnose control blade into a packed pebble-bed with the 45-degree wedge and a pebble-bed height of $48d$. For this experiment, retraction forces were also measured by rearranging the force sensors on the blade holder. Figure 8 shows this hysteresis of the insertion forces, as well as the forces required to retract the blade from the pebble-bed.

Figure 8. Insertion and retraction force profiles for five successive insertions/retractions without intermediate bed mixing. Larger forces are due to blade insertion, while smaller forces are due to retraction. Tests performed using the 45-degree wedge, a pebble-bed height of $48d$, and the 45-degree two-angle no-bullnose blade.

The hysteresis in blade insertion forces can be seen to affect the shape of the force profile in Figure 8. At a blade insertion of approximately $15d$, the insertion forces for all five tests appear to converge. Figure 9 shows that the maximum forces of all tests are nearly constant.

Figure 9. Maximum insertion and retraction forces for five successive blade insertion/retraction force tests without intermediate bed mixing. Tests performed using the 45-degree wedge, a pebble-bed height of $48d$, and the 45-degree two-angle no-bullnose blade.

This data indicates a significant reordering of the pebble-bed due to a blade insertion. It is hypothesized that the initial randomly packed pebble-bed would have many pebbles directly over the center of the blade, resulting in a sharp immediate increase in force as the blade contacts the pebble-bed. It is thought that as the blade is retracted from a fully inserted position, pebbles on either side of it would bridge over the blade center. The reorganized pebble-bed would have stress chains that are much easier to break by the control blade, providing less resistance to motion during a secondary blade insertion event.

3.1.2 Blade Tip Jamming vs. Drag Force

As a blade is pushed through a granular media, it experiences two major forces. The first force is created by the kinetic jamming of pebbles at the tip of the blade. This force is imparted to the tip of the blade by the stress chains in the granular media. The second force is a frictional force on the blade created by the lateral hydrostatic bed pressure that the pebble-bed exerts on the flat surface of the blade.

An understanding of these two forces and how they differ is crucial to the design process of control blades. To the author's knowledge, a separate measurement of each force for a geometry similar to the CoBIE control blade has not been previously reported in the literature.

The aforementioned hysteresis study can be interpreted as indicative of the relative magnitude of these two forces. The insertion force of a blade measures both the kinetic jamming forces exerted by the pebbles on the tip of the blade, as well as the frictional resistance to motion exerted on the sides of the blade. The retraction force of the blade is dominated by the frictional resistance to motion. The measurements of insertion and retraction forces seen in Figure 8 and Figure 9 would therefore indicate that the tip jamming force is much larger in magnitude than the frictional resistance to insertion. Consequently, the blade insertion force is likely to be transferred primarily

to the pebbles at the tip of the blade. This is an important implication when estimating the force that pebbles are subjected to.

3.2 Effects of Blade Angle and Tip Design

The maximum insertion forces for all blades studied by the CoBIE experiment can be seen in Figure 10 and Figure 11. The blade with the least maximum insertion force was found to be the 45-degree 3-angle full-bullnose blade (Figure 10). For both the 2 and 3-angle blade variants, the 45-degree blade tip appears to be the tip angle that results in the least maximum insertion force. The exception is the 45-degree 2-angle non-bullnose blade which is observed to have a very large maximum insertion force. This exception was verified as an accurate measurement by several tests.

Figure 10. Maximum insertion forces for all full-bullnose blades studied.

Figure 11. Maximum insertion forces for all non-bullnose blades studied.

Another notable result shown in the above figures is the large maximum insertion force measured for the 75-degree blades and the 5-angle blade variant. It is hypothesized that these blades require such large insertion forces because their longer leading edges are in contact with more stress chains in the pebble-bed at any given moment.

Tomography tests were conducted to observe how the 45-degree 2 and 3-angle full bullnose blades and the 75-degree 3-angle blade full-bullnose blade affected the pebble-bed. The digital renders of each tomography test can be seen in Figure 12, with pebble color and transparency mapped to respective displacements. The pebbles are rendered with transparency factors inversely proportional to their displacement (stationary pebbles are more transparent). The transparency mapping helps ensure that dynamic portions of the bed may be visualized more easily. The digital renders were generated using X-PETS, code version R2015b. The final blade position is shown outlined in blue. Each render was generated from five timesteps (blade positions) yielding a total blade displacement of 1 pebble diameter. The difference in vertical blade position between each timestep is $\frac{1}{4}$ of a pebble diameter. Pebbles are only rendered if tracked for all five timesteps, resulting in a high confidence in the accuracy of the tracking algorithm. Some pebbles far from the blade in the y-direction were not rendered, in order to better display the relevant area directly surrounding the blade.

A concentration of pebble displacement can be observed around the leading edge of each blade. Some pebbles can also be seen displaced a large amount relatively far from the blade leading edge. This observation can be attributed to one of two hypotheses. The first hypothesis is that the stress chains resisting blade motion traverse a large distance from the blade tip, and the weakest connection in the stress chain (the connection that is broken) can be far from the blade. Based on descriptions of stress chain propagation in the literature, this is a reasonable theory. The second hypothesis is that voids exist in the pebble-bed, and during a blade insertion, pebbles far from the blade can fall into voids, undergoing a significant displacement.

Figure 12. Pebble displacement renders using X-PETS R2015b for $\Delta\text{Blade}=1d$ in a square instrumented 3100 pebble channel with side length $10.5d$ in a larger non-instrumented bed of $H=48d$. Pebbles and blade outline (blue) shown in their final positions. Left: 45-degree 3-angle full bullnose blade. Middle: 45-degree 2-angle full bullnose blade. Right: 75-degree 3-angle full bullnose blade. In this figure, the z -axis origin is defined based on the x-ray imaging region, and is not consistent with the z/d origin in the insertion force results.

4 Discussion of CoBIE Results

4.1 Control Blade Insertion Force and Pebble Fracture

Insertion forces for the blade with the least maximum insertion force are shown by the Weibull distribution function in Figure 13. The insertion forces are dimensionalized by a single Mk1 PB-FHR pebble body force, buoyant in 650°C flibe, as calculated in Section 2.2.

Figure 13. Insertion force probability density function (left) and cumulative distribution function (right) for the 45-degree 3-angle full-bullnose blade being inserted into a pebble-bed with height $48d$. Forces are scaled by a buoyant Mk1 PB-FHR pebble body force= 0.0302N . Weibull distribution variables are 0.1708 kN (scale parameter) and 6.7016 (shape parameter).

Comparing the insertion force distribution to the calculated maximum compressive load limits seen in Table 3, it is shown that a single pebble could be loaded with the entire maximum insertion force measured by CoBIE, and still remain under the compressive load limits with a safety margin.

Table 3. Best-estimate maximum diametrically compressive load limits calculated for a single 3.0-cm fuel pebble by Buster et al. (2015).

Loading Scenario	Maximum Allowable Applied Force (kN) on a 3.0cm Mk1 PB-FHR Fuel Pebble Based on Maximum Internal Tensile Stress
Steel Plate on Pebble (Crushing Test)	5.9 ± 0.3
Pebble on Pebble	5.6 ± 0.3
Steel Control Blade on Pebble	1.19 ± 0.06

Examining the displacement distributions in Figure 12, these results indicate a large safety margin for fuel mechanical integrity. The large leading edge of the control blade is observed to displace many pebbles. The maximum compressive force on a single pebble is therefore highly unlikely to result in fracture.

The limits set forth in Table 3 make the conservative assumption that a pebble is under diametrical loading conditions. In other words, it is assumed a pebble is compressed by two loading surfaces on opposite sides of its diameter. Mixed loading conditions, as would be the case in a pebble-bed, are not considered.

One consideration to increase the likelihood of an even force distribution is to maintain a blade tip angle parallel to the bed interface plane. That is to say, if the central reflector that contains the control blade channel has a 45-degree interface plane with the pebble-bed, the blade should have a

tip that matches this angle. This would ensure that the initial contact force between the blade and the pebble-bed is evenly distributed upon initial contact.

4.2 Assessment of Scaling Distortions

4.2.1 Test Silo Limitations

The distortions created by the limited size of the CoBIE pebble-bed silo must be considered. Both the silo area and height have the ability to provide distortions. Narrow containers such as CoBIE can exhibit significant effects from the walls, and the limited bed height of CoBIE is not fully representative of a full-scale Mk1 PB-FHR core. Similar scaling distortions have been assessed by Rycroft, C. H. et al. (2013) by studying scaled pebble-beds, although the work focused primarily on flow effects.

In a narrow container such as the CoBIE test silo, the walls have the potential to carry a large amount of the vertical bed load due to friction. Landry et al. (2003) has shown asymptotic behavior in vertical bed pressure using DEM simulations, although this phenomena can be traced back to the German engineer H. A. Janssen, with translation provided by Sperl, M. (2005). During blade insertion into the CoBIE test silo, this phenomena would result in insertion forces reaching an asymptote as the bed height increased. The maximum bed height achievable in the CoBIE test silo is $48d$ (48 pebble diameters). Figure 14 shows that the maximum insertion force increases approximately linearly with pebble-bed height. This shows that up to the maximum CoBIE bed height, the container walls do not support a significant portion of the vertical load. The slope of the curve in Figure 14 likely changes as H/d approaches the lower limit because the tip of the blade approaches the top free surface of the pebble-bed at this extreme.

Figure 14. Maximum insertion forces vs. pebble-bed height for three different blade designs.

It must also be taken into consideration that the maximum bed height of $48d$ is approximately half of the bed height in the Mk1 PB-FHR design (Andreades et al., 2014). Assuming no asymptotic loading behavior in the Mk1 design, the actual control blade insertion forces could be twice as large as the forces observed by CoBIE. Based on the insertion force profile seen in Figure 13 and the

maximum load limits in Table 3, the maximum insertion forces for a bed fully scaled to the Mk1 PB-FHR height would still be well below the load limits in Table 3.

4.2.2 Velocity Distortions

During a reactor shutdown event in a typical light water reactor, control rods are inserted very rapidly. In a pebble-bed direct control element insertion event, a major concern is that a very fast blade insertion velocity would cause a much larger force to be imparted to pebbles, possibly increasing the fracture probability.

CoBIE has the capability to test a limited range of control blade insertion velocities. The maximum and minimum insertion velocities are constrained by the maximum and minimum operating speeds of the linear actuator. Because the X-PREX facility was designed to study slow dense granular flow, the linear actuator was not designed for high-speed actuation.

Figure 15. Maximum insertion force for four insertion velocities. Tests performed using the 45-degree wedge, a pebble-bed height of $48d$ and the 45-degree 2-angle full-bullnose blade.

Figure 15 shows no discernable correlation between velocity and insertion force, over the tested velocity range. This non-correlation can be explained by a low-velocity regime, described by Albert, R. et al. (1999). Drag force on an object is found to be a strong function of velocity only when the object's velocity is great enough to "fluidize" the grains in a packed bed. Drag forces below the bed fluidization threshold are considered to be in a "low-velocity regime", and are not dependent upon velocity. The velocity threshold for the fluidization of a bed is defined by Albert, R. et al. (1999):

$$v_{threshold} = \frac{\sqrt{2gd_g}}{10} \quad (4.1)$$

Where:

- $v_{threshold}$ [m/s] is the threshold velocity over which the bed is fluidized and drag force becomes a function of velocity
- g [m²/s] is the acceleration due to gravity
- d_g [m] is the grain (or pebble) diameter

Equation (4.1) can also be used to calculate the velocity threshold in units of pebble diameters per second as follows:

$$\frac{v_{threshold}}{d_g} = \frac{1}{10} \sqrt{\frac{2g}{d_g}} \quad (4.2)$$

For CoBIE, the velocity threshold is calculated to be approximately 4 d/s, which as expected, is greater than the upper limit of the actuator velocity.

If the control blade insertion velocity in the Mk1 PB-FHR system is specified to be faster than the velocity threshold calculated using equation (4.1), additional measurements taken in the fast velocity regime must be performed to ensure sufficiently low forces are imparted to the fuel pebbles.

4.2.3 Pebble Surface Characteristics and Coolant Flow

The static Coulomb friction coefficient was evaluated for instrumented CoBIE pebbles (polypropylene with tungsten wire inserts) on several plastic surfaces, and can be seen in Table 4. A simple ramp test was performed, which consisted of a pebble-holder (the ramp) resting on a flat surface. The pebble-holder was designed to create an ideal pebble-on-ramp contact for friction characterization. The flat surface was inclined until the pebble-holder started to slide. The critical angle was measured to indicate the static coefficient of friction (Laufer and Buster, 2015).

Table 4. CoBIE/X-PREX pebble surface static friction measurements (Buster and Laufer, 2015).

Sheet Material	Static Friction Coefficient ()
Polypropylene (Pebble Material)	0.29
Cast Acrylic (Container Material)	0.39
Polycarbonate (Blade Material)	0.41

The friction coefficients for a graphite-on-graphite contact in molten salt (FLiNaK) were measured by Hong et al. (2009), and can be seen in Table 5.

Table 5. Graphite-on-graphite experimentally measured static coefficients of friction in molten salt (flinak) (Hong et al., 2009).

Temperature [°C]	Normal Mass [kg]	μ_s	σ
492	0.915	0.27	0.04
	1.39	0.26	0.03
	1.86	0.25	0.017
525	0.915	0.26	0.04
	1.39	0.25	0.03

	1.86	0.26	0.017
559	0.915	0.25	0.04
	1.39	0.25	0.03
	1.86	0.25	0.017

The static coefficient of friction between fuel spheres lubricated by a molten salt is approximately to be 0.25, while the coefficient of friction between dry polypropylene is approximately 0.29. Drag and blade insertion forces are therefore expected to be larger in the CoBIE tests compared to forces in a PB-FHR, although the distortion is likely very minimal.

Another parameter that governs properties in a granular bed is the coefficient of restitution (Behringer et al., 1999). Laufer and Buster (2015) reported coefficient of restitution results for the instrumented CoBIE pebbles (polypropylene with tungsten wire inserts). To the author's knowledge, the coefficient of restitution of graphite fuel spheres in an actual reactor system is unknown. The scaling distortion due to varying coefficients of restitution is therefore not currently possible to quantify.

The effects of coolant flow through the pebble-bed during blade insertion were not studied by the CoBIE system. In the Mk1 PB-FHR design, the coolant flow path is directed upwards, in the same direction as the buoyant force. It is anticipated that the coolant pressure drop across the core will be directly related to an increased hydrostatic bed loading force, and therefore an increased blade insertion force. This effect is not yet quantified.

5 Conclusions and Recommendations for Future Work

The Control Blade Insertion Experiment (CoBIE) is a dry, scaled study of direct control element insertion in the Mk1 PB-FHR (Andreades et al., 2014). The experiment measures both the forces required for control blade insertion into a packed pebble-bed and the pebble displacement in response to such an insertion.

A total of 18 blade tip designs were tested, with results presented in Section 3.2. Given the limited number of blade tests, a control blade with a 45-degree 3-angle tip design and fully rounded edges is supported as the optimal blade design for minimizing blade insertion force. While the maximum insertion forces of the 18 blades were often similar when considering experimental uncertainties, all of the scaled insertion forces are well below the limits for the diametrical loading of a 3cm graphite fuel sphere, as calculated by Buster et al. (2015). It should also be noted that the preceding statement includes the conservatism that the insertion force is assumed to be concentrated on a single pebble. It is estimated that for the full core height of the Mk1 PB-FHR, the blade insertion force would remain below the compressive load limits of the fuel elements.

These results support the use of direct control blade insertion as a viable reactivity control method for PB-FHRs, although further work would have to be performed to develop a complete technical safety basis. For example, the analysis of compressive force limits performed by Buster et al. (2015) for 3.0 cm graphite fuel spheres would have to be validated experimentally, in order to provide an accurate probability of fuel failure during a control element insertion event. With an experimentally validated compressive force limit, the risks of fuel failure by direct control element insertion could be appropriately quantified. Furthermore, an extended study using simulation tools would be beneficial to further confirm the CoBIE results presented in this paper. For example, a DEM software package could perform simulations to help quantify the CoBIE scaling distortions, similar to the work performed by Rycroft, C. H. et al. (2013). Simulation work supporting the CoBIE experimental results could also provide additional data unavailable in the X-PREX facility.

Specifically, the maximum individual contact force experienced in a pebble-bed during a high-velocity blade insertion is overwhelmingly difficult to measure experimentally. This data would be paramount in the development of a technical safety basis for the use of directly inserted control elements in pebble-bed reactor cores.

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