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Study on the Thermally-Induced Stress and Relaxation of Ceramic Breeder Pebble Beds

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Abstract — *Ceramic breeder pebble beds undergo complex thermally-induced stress build-up and relaxation processes during reactor operations due to the pebble bed thermal expansion and creep deformation. Understanding such processes can facilitate the evaluation of a solid breeder performance, including bed stress/strain equilibrium status, which will* guide the design of stable blanket operation and assessment of lifetime. *The efforts of this study cover both experimental testing and numerical modeling for this purpose. Measured stresses in pebble beds show a decreasing trend with thermal cycles, until ultimately reaching a saturated state. This stress relaxation is mainly caused by the combined effect of bed plastic rearrangement and accumulation of creep deformation under compressive stresses and high temperatures. As bed stress is reduced, the creep deformation becomes less significant and further cyclic operation would not alter the pebble bed mechanical state. To validate the thermally-induced stress and its variation with cycles, experiments of thermal stress measurement have been designed and conducted for pebble beds heated by both continuous and pulsed power sources. Moreover, the effects of mechanical pre-compaction were investigated with emphasis on understanding the relationship between the bed stress-state evolution and maintaining adequate levels of thermal contact between the pebbles and the coolant structure. The results of this study presents valuable data to serve as a basis for validation of the most recent pebble bed numerical models.*

Keywords — *Ceramic breeder pebble bed, thermomechanics, pre-compaction, stress-relaxation.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Current ceramic breeder blanket designs consist of alternating layers of lithium ceramic material, e.g. Li_2TiO_3, and the neutron multiplier beryllium, Be, both in the form of pebble beds. In the course of blanket operation, stresses are generated due to the differences in both temperature distributions and thermal expansion coefficients between the pebbles and the confining walls, in addition to irradiation-induced swelling. Ceramic breeders operate in a relatively narrow temperature window and therefore these stresses may have a negative impact on blanket performance from such phenomena as temperatures increase due to pebble breakage.[1] While thermal creep in pebble beds is expected to partly release stress build-up, the combined effect of a substantial stress relaxation and plastic pebble bed deformation may greatly reduce the wall/bed interface conductance and cause gap generation during blanket shut-down and heat-up, which also may negatively affect heat transfer, and thereby tritium release, performance. Therefore, a firm understanding of the long-term effects of reactor-relevant stress build-up and relaxation is crucial to achieving stable blanket operation.

In order to better describe and predict the interaction between ceramic breeder and beryllium pebble beds and

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the structural material, the characteristic properties of these pebble beds under not only relevant temperature magnitudes, but also the expected temperature gradients must be known. Previous studies have shown that during the first stress increase, irreversible rearrangement of pebbles is the dominant mode of bed deformation.[2] For subsequent stress increases/decreases, pebble bed stress-strain slopes are steeper and closer to that of the first stress decrease, which indicates more prominent elastic deformation and stiffer bed mechanical behavior. Therefore, the magnitude of thermal stresses induced by the imposed temperature gradient is expected to greatly depend on the initial bed stress state and packing configuration. Particularly, pebble beds will undergo more deformation/rearrangement under low initial packing fraction than beds that have experienced comparably higher initial compaction. To that end, pre-test mechanical compaction load, from here on referred to as "pre-compaction," is considered as a design parameter in this study, where its effect on bed thermo-mechanical evolution will be analyzed.

The primary goal of the present investigation is to define an optimal initial pebble bed packing configuration in the attempt to minimize any significant in-pile thermo-mechanical deviations that may jeopardize the mechanical integrity of the pebbles assemblage and/or appreciably deteriorate heat transfer performance and tritium release. For that purpose, this work aims to: (1) quantify and analyze the stresses induced by the thermal expansion of the pebbles under prototypical temperature gradients and fixed mechanical boundary conditions, (2) study the effects of thermal cycling, mechanical pre-compaction, and thermal creep/stress relaxation on the evolution of pebble bed stress levels, and (3) further develop Finite Element Method (FEM) codes to capture all the above-mentioned synergistic effects arising from reactor-relevant temperature distributions.

Two experiments have been executed in this study: (1) a temperature gradient experiment, where the pebble bed is subjected to fusion-relevant cyclic temperature gradients under fixed mechanical boundary; generated stresses are measured for different testing conditions and loading parameters, and (2) a stress relaxation test where the peak stresses measured in the previous experiment are used as initial loads on isothermal beds and allowed to relax to saturation levels under active creep temperatures.

II. TEST APPARATUS AND EXPERIMENTAL CAMPAIGNS

This section summarizes the experimental methodology and objectives, in addition to providing a basic description of the layout and procedure.

II.A. Test Apparatus and Pebble-bed Characteristics

The experiments were carried out in a modified uniaxial compression test (UCT) facility with a hydraulic press and a three-zone electrical furnace at UCLA. The modified setup incorporates an active cooling mechanism for pistons. Pre-analysis was performed to define the piston coolant operating conditions in order to limit the upper piston thermal expansion as well as to decrease the thermal cycling time. A Paratherm (thermal-fluid) temperature control loop was set-up and coolant flow passages were machined in the solid pistons allowing the Paratherm to maintain the pistons at the desired temperatures. An auxiliary heater on the upper test frame piston and coolant in lower piston together allow a temperature gradient of about 320°C across the sample.

The pebble bed temperatures were measured by three fine-diameter thermocouples located in the top, middle, and bottom bed regions. The setup is shown schematically in Fig. 1.

The breeder material tested in this study is lithium metatitanate (Li_2TiO_3) in the form of pebbles. The batch used in this study was fabricated using the slurry droplet wetting method, which the National Fusion Research Institute in Korea (NFRI) adopted in its mass-production process.[3] Table I shows characteristic values of the investigated pebbles.

It was previously demonstrated that UCTs should be performed with bed height to diameter ratio, H/D, less than unity in order to avoid container wall friction effects.[4] Additionally, to maintain the random packing

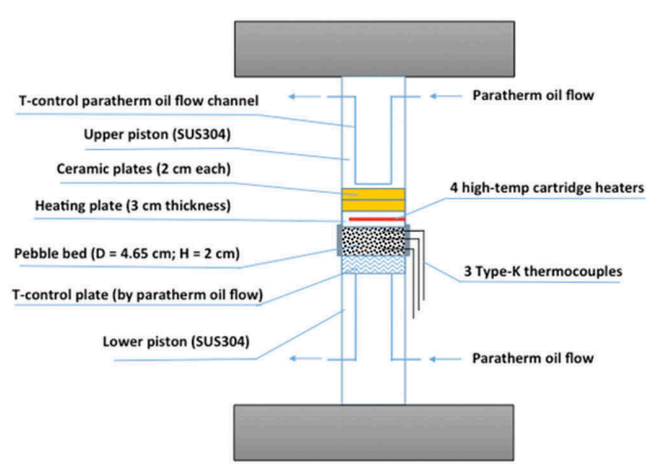

Fig. 1. Updated UCT test stand schematic with cooled piston rods and top heater for cyclic temperature gradient tests.

TABLE I

Characteristics of Investigated Granular Material

Type	Association	Pebble Diameter d (mm)	Grain Size (μm)	Sintering Temperature T_s (°C)	Crush Load (N)
Li_2TiO_3	NFRI	1.03	10	1000	33

of the pebbles in the bulk region of the bed, the bed diameter to pebble diameter ratio, D/d and H/d, have to be greater than 10. Therefore, the pebbles were filled in a cylindrical container with an inner diameter of D = 46.5 mm and a bed height of H = 20 mm, adhering to the recommended dimensions characteristic of blanket relevant shallow pebble beds.

II.B. Temperature Gradient Test

The experiment primarily aims to quantify stresses generated by pebble beds due to prototypical solid breeder blanket temperature gradients and magnitudes under fixed mechanical boundaries. The experimental procedure was established to separate expansion of the piston-heater assembly from that of the pebble bed by heating the upper assembly to an equilibrium temperature before the heater makes contact with the pebble bed, and controlling the power to maintain a constant surface temperature boundary. The procedure defined below is to study pebble bed thermo-mechanics evolution for a fixed boundary configuration.

First, the bed is packed and vibrated to reach a packing fraction of 63% with the thermocouples installed in the designated positions in the bed (top, middle, and bottom regions), piston (at the mid-plane location), and heater. After applying a pre-compaction load, defined in Table II, at room temperature for 5–10 minutes, the upper piston is separated from the bed, heaters energized, and brought to target steady-state temperature while the coolant circulates through the upper and lower pistons. Next, the piston is lowered to make contact with the pebble bed whereupon the crosshead location is fixed and recorded for use in subsequent thermal cycles to simulate the fixed mechanical boundary of the blanket coolant structure. To minimize heat losses, the pistons are wrapped with insulation, and the furnace is closed during bed heat-up phase. Additionally, a Labview feed-back loop controls the heater power level to maintain a constant heater surface temperature throughout the full experimental procedure. As the bed heats up from room temperature to the final gradient, bed temperatures and the thermally-induced forces are monitored until all values reach steady-state. Finally, the piston is retracted, heater remains energized, and the bed is actively cooled to the initial baseline temperature. The above procedure is then repeated for any subsequent thermal cycle with the upper piston brought down to the fixed crosshead height, as recorded from the first thermal cycle, rather than a target contact load.

TABLE II

Temperature Gradient Test Parameters and Testing Conditions

Initial Packing Fraction γ (%)	σ_{pc} (MPa)	Measurement Pre-Compaction (μm)	Temperature Difference[a] ΔT (°C)	σ_{p1}[b] (MPa)	σ_{p5} (MPa)
63.2	0.1	–	288 [450–162]	0.25	0.005
63.5	1	366	300 [457–157]	0.98	0.03
63.1	2	446	311 [474–163]	1.8	0.82
63.2	3	597	318 [477–159]	1.92	1.85
63.3	0.1	–	391 [659–268]	0.54	0.04
63.3	3	580	402 [657–255]	3.1	2.89

[a]Bed temperature difference at end of cycle [average top bed temperature – average bottom bed temperature].
[b]σ_{pi} → i'th thermal cycle peak stress.

II.C. Stress Relaxation Test

Past studies on stress relaxation revealed that for a bed temperature of 770°C, the uniaxial pressure drops to 25% of the initial value during only the first two hours.[4] However, pre-compaction effects were not considered in those studies. Therefore this second experimental campaign aims to further investigate pebble bed stress state evolution under different creep-relevant temperatures, initial loads, and pre-compaction levels. The three-zone furnace, incorporated in the UCT test stand, is used to raise the bed temperature until reaching steady state, while the temperature controller is used to independently power each zone based on the continuously monitored bed thermocouples to guarantee uniformity. An initial load is applied, after which the bed volume is fixed while allowing the stresses to relax as creep deformation takes effect.

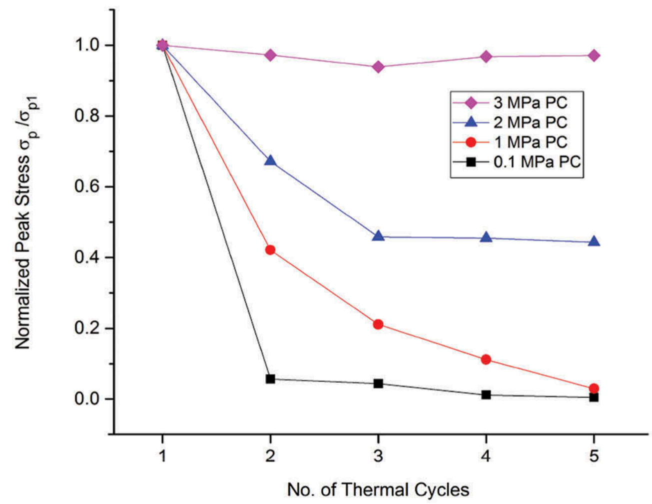

Fig. 2. Thermally-induced peak stresses normalized by first cycle peak stress for different pre-compaction loads show higher pre-compaction lead to more stable stresses during thermal cycling.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The results of both tests are presented in this section, followed by extensive analysis of the observed phenomena.

III.A. Temperature Gradient Test Results

Five thermal cycles were carried out at four levels of pre-compaction and two bed temperature states. The experimental matrix, as well as the measured peak stress magnitudes for the first and last cycles are summarized in Table II. The peak uniaxial stresses measured at the end of each thermal cycle were recorded for different pre-compaction levels to test effects of pre-compaction on the stability of generated stresses as the number of thermal cycles increased. Figure 2 shows that the reduction of initial peak stress is much more significant for lower pre-compaction. In other words, higher levels of pre-compaction show a more stable behavior during subsequent thermal cycling compared to lower pre-compaction levels. For the 0.1 MPa pre-compaction case, stresses diminished after the first cycle for the two bed temperature states tested, indicating a gap generation at the top of the pebble bed. In contrast, for the highest pre-compaction run of 3 MPa, generated stresses remained practically constant throughout the thermal cycling process. For the 1 MPa case, the stress magnitudes were larger than those for the 0.1 MPa case, but still deviated significantly from the initial cycle stress and continued to drop with cycling. For the 2 MPa case, the stress level dropped to about half the initial value, but remained stable after the third cycle.

III.B. Stress Relaxation Results

Figure 3 shows initially-applied stresses relaxing with time for different pre-compaction levels and uniform bed temperatures. A sudden drop in axial stress is observed for the high temperature cases (T > 650°C) as soon as the bed's volume is fixed. For T = 650°C, this drop seems to be less abrupt for pre-compacted beds, denoting a stiffer bed response. Nonetheless, after the initial steep drop phase, it is evident that the relaxation process is primarily governed by a relatively slower creep deformation, which saturates to stable levels after approximately the first 5 hours ($\sigma_{sat} \approx \sigma_{5hr}$). Since creep is thermally activated, temperature was, unsurprisingly, the most sensitive parameter controlling the rate of stress decay. Thus, for the 750°C case, stresses dropped faster and saturated slower than those for the 650°C cases. For the highest temperature run of 850°C, axial stress dropped from 4 MPa to 0.1 MPa in less than 4 hours. By comparing the two runs of initial stress of 4 MPa and 2 MPa at 750°C, a slower rate of stress relaxation is observed for the lower initial stress level.

III.C. Discussion & Analysis of Results

The above results can be explained by analyzing the mechanisms of multiple effects/interactions of plastic

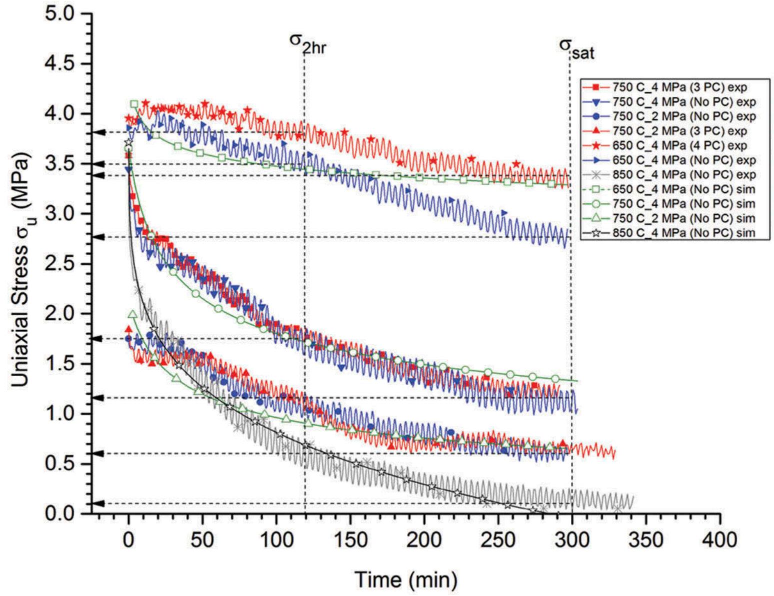

Fig. 3. Stress-release by thermal creep for different temperatures, initial loads, and pre-compaction.

deformation, thermal expansion, and creep in granular materials. Pebble beds irreversible or plastic deformation takes place mainly due to bed consolidation, which typically arises when the bed undergoes compressive stress states, causing pebbles to rearrange into denser packing configurations. This behavior prevents the bed from recovering to its initial configuration and increases its overall stiffness. It has been demonstrated experimentally as well as numerically that the highest levels of bed plastic deformation occur over the first few loading/unloading cycles, followed by mostly recoverable elastic strains for subsequent cycles[5] – provided that the applied/generated stress does not exceed the initial load, as demonstrated in Fig. 4. Hence, the temperature gradient experiment runs where pre-compaction load was greater than the thermally-induced stress resulted in the most stable bed stress state with cycling.

Since the highest temperature reached in the first experimental campaign of 650°C (below which no appreciable creep is observed) was only experienced by the few top layers of pebbles in the bed, the second campaign was designed to further assess the stress state stability at creep relevant temperatures. Generally, correlations that predict creep behavior in pebble beds strongly depend on the initial stress level and temperature; higher temperatures/stresses accelerate the strain rate, $\dot{\epsilon}_{v,cr}$, see Eq. (3). Additionally, interesting phenomenon was observed while analyzing the effect of pre-compaction on relaxation rates. In Fig. 3, at 650°C, the threshold temperature of noticeable stress release, no rapid initial stress drop

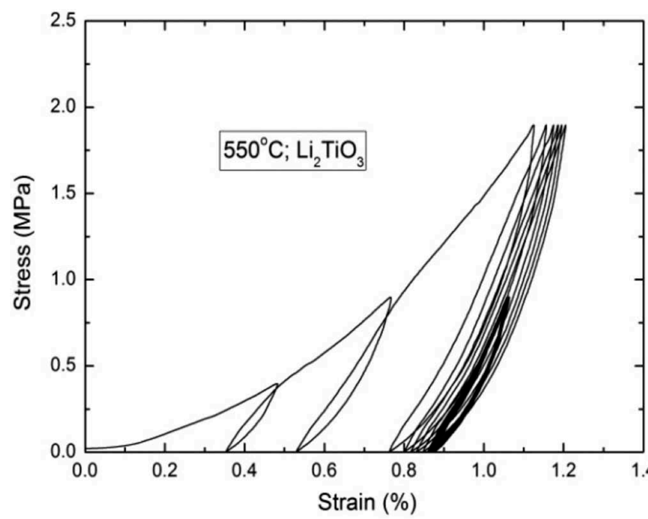

Fig. 4. Pebble bed stress-strain curves of previous UCLA experiments illustrating initial bed plasticity, bed modulus stiffening, and consistent cyclic behavior below yield stresses.[5]

was observed and the stress relaxation saturated faster than that of the no pre-compaction case. On the other hand, at 750°C and above, temperature was the dominant parameter governing the rate of stress relaxation, and the effect of pre-compaction was much less apparent.

To understand this behavior, one must carefully examine the mechanisms of permanent deformation in materials with regards to plasticity and creep. At stress levels below the current elastic limit, there is not enough energy available for the pebbles to rearrange themselves irreversibly. Since pre-compaction enhances the bed's yield strength, a compacted bed will exhibit higher resistance to deformation for the same temperature. Nevertheless, elevated temperatures add thermal energy to the system, increasing the likelihood of permanent deformation. Therefore, at high enough temperatures, there is enough thermal energy available to induce creep and stress relaxation, even if the initial stress level is well below the yield strength of the material. During creep, the contact areas between the pebbles increase and initial gaps may close with compaction. This generates new contacts that transmit a fraction of the load and decreases the average stress per contact surface, resulting in slower strain rate with time.[6] Therefore, unlike creep tests where the experiments take days/weeks to reach saturation, the stress relaxation is expected to saturate faster since the strain rate depends on the current stress state, which is constantly decreasing as more stress is released. This behavior is more relevant to fusion blankets since there will be no constant externally applied loads on the bed.

Although stress relaxation will aid in discharging pressure caused by thermal expansion and irradiation-induced swelling loads in the highest temperature bed zones, a subtle risk stems from its interaction with plasticity in the lower temperature regions. The temperature gradient cycling experiment demonstrated that, for the no pre-compaction cases, the bed pressure drops to practically zero and gaps form at the bed/structure interface after the first few cycles even for the higher temperature runs (RT→650°C). Furthermore, based on the stress relaxation tests, the stresses in the high temperature bed regions will also diminish to much lower levels over the first few hours of operation. Previously proposed and validated thermal models of bed-wall interfacial heat conductance as a function of mechanical stress and gap show strong dependence of the interface heat transfer coefficient HTC on the interface pressure for a fixed bed temperature.[1,7–9] Consequently, if a gap forms at the interface or if the pressure reduces to inadequately low levels with continuous thermal cycling and relaxation, the efficiency of heat extraction at the coolant structure walls can deteriorate, risking an increase in bed temperatures until greater expansion once again resumes stress levels; at which point sintering temperatures may be exceeded and tritium extraction is reduced. Therefore, the results suggest pre-compaction is needed to overcome major stress reductions with cycling in the lower temperature bed regions (T < 650°C), which is characteristic of the near-wall zone, while relying on a self-regulating stress release mechanism in the core region of the bed (T > 650°C) to compensate for the higher thermally-induced stresses and irradiation-induced swelling loads. Moreover, the results also highlight the necessity for future multiple effect experiments on pebble beds in which the myriad modes of thermo-mechanical interaction predicted in solid breeders are all simultaneously active.

IV. FEM METHODOLOGY/MODEL IMPROVEMENT

For a reliable design of fusion blankets with solid breeder and beryllium pebble beds, it is critical to have validated computational tools for predicting thermo-mechanical conditions and evolution over blanket lifetime. The material models currently in use/under development at UCLA to capture pebble bed synergistic effects are: (1) non-linear elasticity, (2) temperature-dependent Extended-Drucker-Prager plasticity model combined with the (3) Cap creep model, in addition to, (4) temperature-dependent thermal properties (thermal conductivity, thermal expansion coefficient, specific heat). Many of the models have had their constitutive equations verified with single-effect exmepriments.[10]

The non-linear elasticity was modeled by defining Young's modulus (E) as a function of two stress invariants, I_1 and J_2, and temperature, T. The material parameters of $A_e(T)$ and s were curve-fitted to experimental data. E_0 is the initial bed modulus, and ν is Poisson's ratio.

$$E = A_e(T)\left[(1+\nu)J_2 + \frac{1-\nu}{3}I_1^2\right]^{s/2} + E_0 \qquad (1)$$

The plasticity cap hardening law was defined through a function of volumetric plastic strain (ε_v^p) and (I_1), which has the exponential form in Eq. (2). The W(T) value is the limiting value of volumetric plastic strain. D1 and D2 values are obtained from curve-fitting the volumetric strain vs. 3*pressure (I_1) experimental data, and (X) is the initial value of X_0 at which the cap takes effect in the plasticity model.[11]

$$\varepsilon_v^p = W(T)\left\{e^{[D_1 - D_2(X-X_0)](X-X_0)} - 1\right\} \qquad (2)$$

A strain-hardening cap-creep model was used to simulate the stress relaxation experiments, in which the volumetric creep strain rate ($\dot{\epsilon}_{v,cr}$) is expressed as a function of equivalent creep stress ($\bar{\sigma}_{cr}$), volumetric creep strain ($\epsilon_{v,cr}$) and temperature (T), shown in

Eq. (3). C_1–C_4 are recalibrated material constants derived from past creep tests to fit stress relaxation data.

$$\dot{\varepsilon}_{v,cr} = C_1 \bar{\sigma}_{cr}^{C_2} \varepsilon_{v,cr}^{C_3} e^{-C_4/T} \quad (3)$$

Figure 3 shows satisfactory agreement with experimental data without including pre-compaction effects. The results of the 750°C cases matched experiments for both stress levels to a great extent. Slight deviations were observed for the other two temperature runs. Specifically, the stresses saturated faster and at a higher level for 750°C, but dropped down to zero at an earlier stage for the 850°C case. Nonetheless, the overall results are promising and encourage further numerical enhancement to prepare for incorporating blanket relevant temperature distributions where phenomena of interest are expected to occur. Furthermore, the FEM modelling is currently being enhanced to overcome numerical convergence problems in order to validate temperature gradient and future multiple-effects experiments.

V. CONCLUSION AND FUTURE WORK

Two experimental campaigns were conducted at UCLA to serve as precursors to future efforts of analyzing the multiple effects/multiple interactions of the various phenomena that occur in a prototypical solid breeder fusion blanket. The temperature gradient thermal cycling experiment considered the combined effects of plastic deformation and thermal expansion under thermal cycling conditions, while the stress relaxation test examined the stability and evolution of bed stresses under creep/reactor relevant temperatures. Emphasis was laid upon understanding potential loss of thermal contact between the pebbles and the coolant structure as a result of the combined effect of stress relaxation and bed plastic deformation.

Pre-compaction was investigated as a design parameter and proved to have the following effects on the bed as a result of bypassing the substantial plastic deformation that normally occurs during the first few loading/unloading cycles: (1) artificially increasing the bed stiffness, and thereby raising the thermally-generated stresses to appropriate levels that maintain good interface contact conductance and pressure, (2) reducing the number of thermal cycles required to reach a state of stress saturation, and (3) mitigating sudden stress reductions in the transitional creep regions of the bed.

Efforts are currently underway to develop a 3D, fully-coupled thermo-mechanical volumetrically-heated, transient breeder cell model capable of simulating an adequate number of thermal cycles to reach stress-saturation levels. The model incorporates all previously validated single-effect material models, permitting preliminary analysis of many synergistic effects of a solid breeder in a typical fusion environment. Nevertheless, there is uncertainty in the predictive capability of FEM simulations until validation against multiple-effect experiments. Therefore, in order to reach more conclusive results, extensive experimental efforts are ongoing at UCLA to analyze the interaction of blanket relevant multiple effects with volumetric heating conditions.

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