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R&D Plan for Addressing the Thermomechanical Behavior of Lithium Ceramic and Beryllium Pebble Beds in Fusion Blankets

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1. Objective of Pebble Bed R&D Effort for Fusion Blankets

Several blanket designs based on lithium ceramic and Be pebble beds are being currently considered for fusion reactors (e.g. refs. [1, 2]). The thermomechanical behavior of the pebble bed regions represents a key issue for these blankets. This is mostly due to temperature-driven processes imposing operating limits on the pebble bed temperatures and requiring acceptable accuracy in the prediction of the pebble bed spatial and temporal temperature profiles over the lifetime of the blanket. For example, the tritium inventory in ceramic breeder and Be increases with decreasing temperature and would set a lower limit on the operating temperature of Be and Li ceramics. For blankets with the possibility of water ingress under safety analysis scenarios the possible Be/steam reaction imposes an upper limit on the Be operating temperature. Differential thermal expansion and swelling creates stress/strain conditions which affect the pebble bed thermal conductivity and possibly the lifetime of the component, and need to be understood.

The ultimate goal of the R&D on the thermomechanics of Be and lithium ceramic breeder pebble beds is to provide the ability to predict with acceptable confidence the thermomechanical behavior of the pebble beds in a blanket design under the whole range of blanket operating conditions in a fusion reactor. This is an essential requirement in finalizing the design of blanket concepts making use of Li ceramic and Be pebble beds.

The R&D roadmap leading to this goal can be expressed in terms of modeling and experimental activities. It is clear that these activities are complementary and cross-linked with a flow of input/feedback information between them guiding the ensuing R&D phase. Over the last 10-15 years, much R&D activity has been pursued in this area with differing focusing level on the final goal; results from R&D are often of academic interest and represents some useful contribution per se but, here, for this specific R&D rodmap, one must not lose track of the ultimate goal described above.

2. R&D Roadmap

Figure 1 shows an attempt to simplify and summarize in a roadmap the elaborate and detailed R&D effort required to achieve the final goal. The effort is divided in modeling and experimental activities, which are further divided into distinctive (albeit interconnected) efforts on determining the effective thermal conductivity and the stress/strain behavior of pebble beds. For simplicity, no differentiation is made in evolving this roadmap between lithium ceramic and Be beds. Be beds have a much higher ratio of k_s/k_g than lithium ceramic beds, and, consequently, their k_{eff} is much more influenced by factors affecting the solid to solid heat transfer, such as the contact area and surface roughness. In addition, Be swells appreciably under irradiation, further complicating the behavior of the bed. Thus, a complete R&D effort is needed to fully characterize the Be bed behavior and be able to predict with confidence its behavior under the range of blanket operating conditions.

It is believed that a somewhat smaller effort would be required for Li ceramic beds but still covering to an acceptable level all issues shown in Fig. 1 to also provide the necessary confidence in predicting their behavior.

Details of the roadmap shown in Fig. 1 are explained below. Note that there is a constant interrelation (input/feedback) between modeling and experimental activities and within these activities themselves.

2.1 Identification of Key Parameters

The first step is to identify the key factors and parameters affecting the pebble bed k_{eff} and stress/strain behavior, which will guide the modeling and experimental effort. These parameters can be identified based on first principle but have also been confirmed through the interpretation of earlier modeling and experimental R&D effort. They are described below not in order of importance but rather separated for clarity between parameters that have more impact on k_{eff} and those with more impact on the stress/strain behavior, the former being arbitrarily listed first.

2.1.1 k_s/k_g

The ratio of solid to gas conductivity plays a key role in determining the heat flux path through the pebble bed, and, hence, k_{eff}. When this ratio is low, about 1-10 (e.g. for some lithium ceramic bed with He), the heat flux tends to be more uniform across the solid and gas regions of the pebble bed. When this ratio is high, 10-100 or more, the heat flux tends to

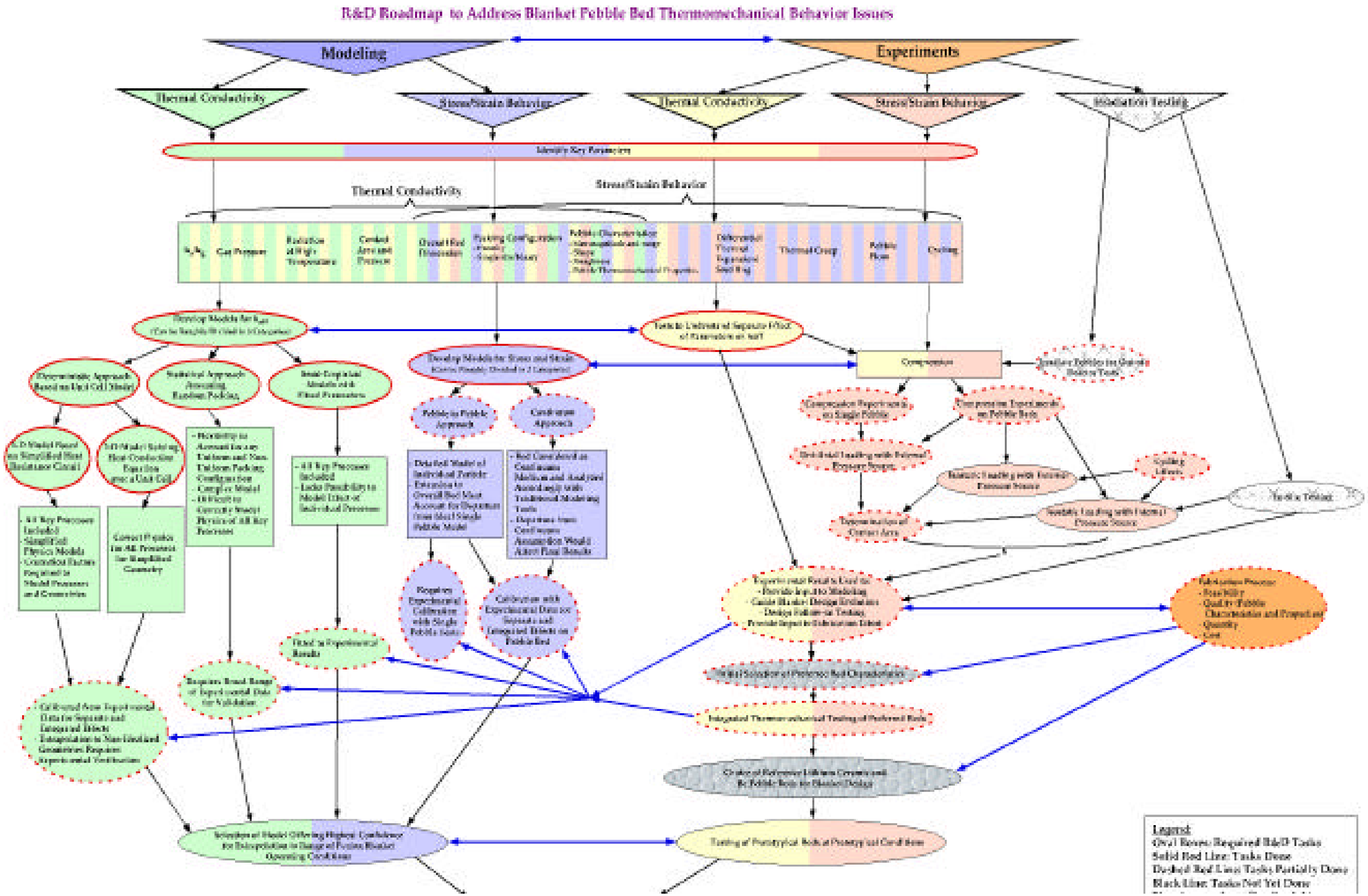

Figure 1 R&D Roadmap to Address Li Ceramic Blanket Pebble Bed Thermomechanical Issues

follow the path of least resistance and would be curved in the solid pebble region focusing at the point of contact between pebble beds. Thus, beds with high ratio of k_s/k_g would be more affected by change at the contact region.

2.1.2 Gas Pressure

The gas pressure is important as, in combination with the local characteristic dimension, it determines the Knudsen number (the ratio of mean free path of the molecules to the local characteristic dimension). The gas is in the Knudsen (molecular) regime for Knudsen number higher than about 0.1-1, and the gas conductivity in this regime is lower (Smolukovski effect [3]) with a corresponding effect on k_{eff}. This effect is more pronounced for smaller pebble dimensions and for higher ratios of k_s/k_g. It was even suggested to use this effect as a possible active control mechanism, whereby, if needed, the effective thermal conductivity of a Be/He pebble bed in a fusion blanket could be adjusted to account for uncertainties, change in properties or power variations [3, 6]. For example, initial analyses indicated that the k_{eff} of a 0.1 mm Be/He bed can be varied by factors of about 1.5 to 1.8 by changing the He gas pressure between 0.2 bar to 2 bar [3]. However, this effect would be greatly reduced as the contact area is increased (for example due to plastic deformation under differential thermal expansion and/or swelling); due to this and to other practical considerations, this idea was not further pursued in this context.

2.1.3 Radiation

Radiation heat transfer could play a significant role at high temperature (> ~ 500-600°C) depending on the pebble material and surface emissivity [7]. Thus, it should be included for an accurate prediction of the bed k_{eff} at high operating temperature.

2.1.4 Contact Area and Pressure

The contact area between pebbles plays an important role in determining the heat flow path through the bed, and increasingly so for high k_s/k_g ratio, such as for Be/He beds. The combination of the contact area, the nature of the contact (dictated by the contact pressure) determines the fraction of the total heat transfer flowing through the contact, and, consequently, the impact of the contact region on k_{eff}.

2.1.5 Overall Bed Dimension

The overall bed dimension is important relative to the pebble size as it would determine the relative influence of the near surface regions as compared to the bulk region. Typically, the near surface region would have a somewhat different packing arrangement and porosity and, thus, thermomechanical behavior. It is desirable that the overall thermomechanical behavior of the bed be governed by the uniform bulk region (usually with a more predictable behavior); thus, the ratio of overall bed dimension to pebble size should be high (10-100).

2.1.6 Packing Configuration

The bed porosity and packing arrangement (single size or binary) are considered under this category.

Porosity: The porosity is related to the packing technique but also to the pebble mix (i.e. single size or binary packing), the pebble size in relation to the bed dimension, and the range of pebble sizes (departure from the average size). In that sense, it is not really an independent parameter but does affect the bed k_{eff} and stress/strain behavior through the sheer distribution of solid and gas in the bed.

Single or Binary Packing: Single size packing would typically result in a porosity of about 39%, mostly as an orthorhombic arrangement but with some departure from this depending on the packing procedure (vibration characteristic and duration) [4]. Adding a smaller size pebble (typically smaller by a factor of 5-10) would result in much lower porosity (~15-20%). This would affect the thermomechanical behavior of the bed both by influencing the porosity and though the particle to particle interaction in particular for binary beds.

2.1.7 Pebble Characteristics

The pebble characteristics can be divided in a number of specific parameters describing the pebble and individually affecting the heat transfer and, hence, k_{eff}, and the particle to particle interaction and stress/strain behavior under loading conditions.

Pebble Size Magnitude and Range: The size of the pebbles is an important parameter. In relation to the size of the pebble bed region, it dictates the corresponding influence of the near-wall region where local change in the packing geometry would affect the heat transfer performance and the stress/strain behavior in particular for model based on the continuum approach. It also sets the local distance between adjacent pebble over a unit cell; this is an important parameter determining the local Knudsen number and influencing the local thermal conductivity of the gas if operating in the Knudsen (molecular) regime where the Smolukovski effect is important [3]. The range of sizes can have an important impact on the thermomechanical behavior. This is different from having a binary bed for example (dual-size pebbles) but reflects the range of sizes around the average size, usually dictated by the selected fabrication procedure. Many models tend to be evolved for homogeneous and single size beds. Thus, departure from this would have to be included in these models.

Shape: The shape of the pebble is mostly dependent on the fabrication procedure, the final selection of which will be based on a quality requirement versus cost exercise. This is important for models based on a simple spherical geometry. For example, for such models for k_{eff}, moderate departure from sphericity should have a minor effect on the heat transfer performance through the solid. However, departure from sphericity that could affect the contact area could have a major effect. Under lower stress, any particle relative motion could depend on the smoothness and shape of the pebble, influencing the bed stress/strain behavior.

Roughness: Both the roughness height and density can play an important role in characterizing the nature of the solid-to-solid contact. This would influence both the contact thermal resistance which influence k_{eff}, and the pebble to pebble interaction which influences the bed stress/strain behavior. For example, over the interfacial area, at low pressure, the roughness density determines the actual solid-to-solid contact with gas trapped between the roughnesses over a thickness dictated by the roughness height. At higher pressure this gap is reduced and the contact conductance is increased [5]. The roughness characteristics would also have an influence on the heat transfer along the pebble circumference but this effect on k_{eff} would be relatively small.

Pebble Thermomechanical Properties

The pebble mechanical properties (yield strength, Young’s Modulus, hardness, Poisson’s ratio etc…) would have a direct bearing on the stress/strain behavior of the bed while the thermal conductivity of the pebble will influence k_{eff}.

2.1.8 Differential Thermal Expansion/Swelling

Differential thermal expansion and irradiation swelling provide the internal force compressing the pebble bed and are the main instigator of stress and strain in the bed.

2.1.9 Thermal Creep

Due to the relatively small pressure-transmitting contact area between pebbles, large local stresses are experienced even when the overall pressure on the bed is moderate. In most cases these stresses exceed the elastic limit and the material starts to yield. Plastic deformation then increases the contact area and reduces the load. Further creep relaxation might reduce the load even more while maintaining the contact area. In that sense, creep would provide some benefit as it might prevent pebble fracture by allowing for local stress relaxation, and increase lifetime of the pebble bed region. However, it can also affect the thermal conductivity of the bed as relaxation occurs with possible particle shift and change in contact area and/or pressure.

2.1.10 Pebble Flow

This refers to the motion of the pebble bed during loading where it effectively acts like a fluid. This is an important factor which must be properly characterized and modeled to help understand the bed thermomechanical behavior.

2.1.11 Cycling

Cycling will affect the stress/strain behavior of the bed mostly due to plastic deformation and creep. During the loading part of the cycle, the pebble might deform plastically at the contact if the yield stress is exceeded locally, thereby increasing the pebble to pebble contact area and increasing k_{eff}. During the load reduction part of the cycle, although the stress on the bed is reduced the strain would stay about the same because of plastic deformation. Thus, some hysteresis behavior is expected in particular during the initial cycles.

2.2 Modeling

2.2.1 Modeling Objective

It is clear from this that many parameters will affect the thermo-mechanical behavior of the pebble bed. Different modeling techniques can be used to include the effects of these parameters, ranging from detailed physics model integrated in a more comprehensive overall model to semi-empirical model lumping together separate effects. However, in all cases, these models must be calibrated with experimental data, if possible through separate effect experiments and certainly through integrated experiments.

Ideally, fully prototypical experiments covering the whole range of possible operating parameters would provide 100% confidence in predicting the behavior of the pebble bed blanket under the full range of operating conditions in a fusion reactor. However, because of practicality, cost and laboratory constraints, and also of the possibility of unknown factors, it is likely that the experimental program cannot cover the full range of fusion operating conditions. For example, testing of the pebble bed under end of life swelling and at high temperature would probably not be achieved. This is where the essential function of modeling comes into play. In addition to help understand the impact of different parameters on k_{eff} and the stress/strain behavior, modeling bridges the gap between experimental data and operating conditions. In other words, as illustrated in Fig. 2, it provides the necessary extrapolation with reasonable confidence to predict the thermomechanical behavior of the bed over the whole range of operating conditions. This essential function of modeling can only be achieved if the models are developed to take into account all key parameters including departure from ideal geometry and requires a thorough calibration over the prototypical but somewhat reduced experimental data range.

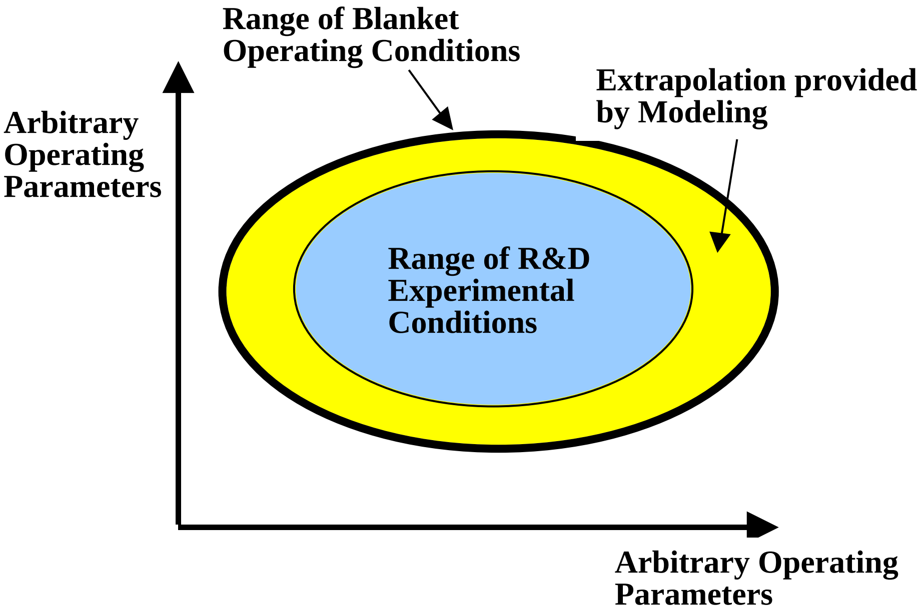

Figure 2 Schematic of Complementary Experimental and Modeling Effort

2.2.1 <u>Modeling Approaches</u>

The modeling activities are divided between models developed for the bed effective thermal conductivity and those developed for the bed stress/strain behavior.

The k_{eff} modeling approach can be divided among:

- Deterministic models focusing on a unit cell of the pebble bed assuming a good degree of packing uniformity;

- Statistical models assuming random packed-bed configuration; and

- Semi-empirical model assuming the basic physics but fitted to experimental data.

The stress/strain modeling approach includes modeling based on single pebble (including discrete models) and modeling based on the continuum approach assuming homogeneous bed behavior. Modeling activities for k_{eff} and for stress/strain are also very complementary. For example, the strain and corresponding contact area calculated from stress/strain modeling can be used as input for k_{eff} modeling.

All models rely heavily on calibration with data from the selected Li ceramic and Be bed configurations for blanket application. This is even more important as the convergence to the selection of the reference prototypical beds progresses. In parallel, the modeling strategy would include a selection of the model offering the highest degree of confidence for extrapolation. This model would then need to be calibrated with prototypical data for the prototypical beds over a large enough range of operating parameters to provide confidence in any required extrapolation.

2.3 Experiments

Packing studies investigating the packing configuration as a function of pebble size distribution and shape and packing techniques (vibration frequency and time) are carried out early to help in characterizing the packing arrangement (e.g. see Ref. [4]).

Other early experiments are focused on testing to understand the influence of separate effects on k_{eff}, including packing configuration, pebble characteristics, gas pressure, temperature, ratio of test section to pebble dimension, and contact area. The stress/strain behavior and resulting contact area is governed in great part by the compressive load arising from irradiation-induced swelling and/or differential thermal expansion under blanket operating conditions. These are internal forces but, for simplicity, the initial experiments in this area are aimed at reproducing the internally-induced strain by applying an external force on the pebble bed and measuring the stress and strain of the bed and the corresponding effective thermal conductivity (e.g. see Refs. [8, 9]).These compression experiments would evaluate the stress/strain behavior for both single pebble and packed bed cases including time-dependent creep at different temperatures. The pebble bed experiments would include simpler uni-axial loading for stress/strain assessment but should also aim at achieving isostatic loading to better model the real situation. Ways of reproducing internal loading perhaps with carefully measured differential thermal expansion should also be considered. In all cases, in addition to measurement of the compressive load on the bed and of the resulting strain and k_{eff}, post-test measurement of the contact radius would be very useful for furthering the understanding of its influence on k_{eff} and for model calibration.

In parallel to these, in-situ irradiation experiments should be done for pebble bed mock-up inserted in a fission reactor with the aim of characterizing the pebble bed stress/strain behavior and measuring its temperature distribution (from which k_{eff} can be obtained) as a function of neutron fluence. Fabrication studies focusing on the feasibility, pebble characteristics, cost and possibility of large-scale fabrication should also be carried out.

Results from all these experiments would help to provide input to modeling, guide the evolution of blanket design, provide feedback to the fabrication process effort and plan for follow-on experiments.

These follow-on experiments would be aimed at providing data over a wide range of operating conditions for the initial selection of Li ceramic and Be pebble bed configurations. Based on these results and on input from the modeling and fabrication development efforts a final decision will be made to select the reference Li ceramic and Be pebble bed blanket configuration. These would have to be tested over a wide range of prototypical conditions to provide confidence in its performance and to provide the required data for model calibration and extrapolation.

3. Status

Important progress has been made over the last 10-15 years from experimental and modeling R&D efforts in the EU, Japan, the USA, and to a smaller extent in Canada, as illustrated in Fig. 1 where the oval boxes drawn in solid red lines represent R&D tasks that have been essentially completed, and the oval boxes drawn in dashed red lines represent partially completed tasks. It must be said that research effort on the thermal conductivity and behavior of porous media has been going on over dozen of years for other applications such as soil analysis and fission sphere pac fuel [e.g see Ref. [10, 11]). Results from these efforts were very useful in jump starting the specific fusion R&D on Li ceramic and Be pebble bed behavior.

On the modeling side, the initial effort focused on predicting the effective thermal conductivity of a pebble bed. The effort built on the wealth of work done previously on pebble bed modeling for other applications. Different modeling approaches were used including statistical and semi-empirical approaches but the deterministic model approach based on a unit cell seemed to have been favored. Deterministic models that were developed range from 1-D model based on the solution of an effective parallel and series thermal resistance circuit (e.g. see Ref. [12, 13]), to quasi 2-D model where 2-D effects are included for example by accounting for the heat flow path convergence at the contact area (e.g. see Ref. [14]), to 2-D and 3-D models reproducing the correct physics for the assumed unit cell geometry (e.g. see Refs. [11, 15, 16]).

More recently, it became clear that, due in part to the major experimental and modeling focus up to then on k_{eff}, there was a lack of progress in addressing the overall thermomechanical behavior of the bed under operation-induced loading in particular differential thermal expansion and irradiation swelling which would affect both the stress/strain behavior of the bed and indirectly k_{eff}. In parallel with a well-planned experimental effort, models were developed over the last 3 years or so to try to bridge this gap and shed more light on the stress/strain behavior of Li ceramic and Be packed beds (e.g. see Refs. [17, 18, 19, 20, 21]).

On the experimental side, the initial effort focused on testing to understand the influence of different effects on ceramic breeder and Be pebble bed k_{eff}, including packing configuration and fraction, pebble size and shape, gas pressure effect (e.g see Refs. [6, 22, 23, 24, 25] and summary results in Ref. [26]). Many of these experiments were performed in cylindrical geometry with a central heater and with thermo-couples to measure the temperature distribution through the pebble bed from which the bed k_{eff} and the effective wall conductance could be measured. Experiments to study the bed packing as a function of packing configuration, vibration and time were also conducted confirming the earlier findings that the arrangement for single-size pebble bed packing is mostly orthorhombic (for which the porosity is 39.5%). It also became clear that for the overall bed thermal conductivity to be governed by the bulk k_{eff} (and not by wall effects), the ratio of test section size to of pebble bed size should be of the order of 10.

These initial experiments were useful in helping to calibrate models in particular for low temperature, low k_s/k_g and point-contact cases. They also confirmed the effect of low gas pressure on k_{eff} (when the gas thermal conductivity in the Knudsen regime) and the importance of contact area in particular for high k_s/k_g beds (e.g Be/He). However, they usually suffered from a lack of detailed characterization of certain conditions including stress/strain and have to be interpreted carefully, tending in some cases to confirm trends more than providing absolute values as a function of specific parameters. For example, it is clear from the experimental results that the contact area has a major effect on the heat transfer in particular for high k_s/k_g beds (Be/He). However, changes in contact area were not well planned and tended to occur due to differential thermal expansion of the test section.

The contact area was not measured but tended to be characterized very roughly by simple differential thermal expansion analysis. Thus, the trend of increasing k_{eff} with increasing contact area was easily identified but it is difficult to provide data linking k_{eff} to a specific contact area, which would help for accurate modeling calibration.

In general, though, it can be said that the combination of these early modeling and experimental activities helped better understand the pebble bed k_{eff} behavior, identify and confirm all the key parameters influencing the thermo-mechanical behavior of the bed, and set the stage for the follow-on effort. However, as mentioned earlier, due in part to this k_{eff} focus, there was a lack of progress in addressing the overall thermomechanical behavior of the bed under operation-induced loading in particular differential thermal expansion and irradiation swelling which would affect both the stress/strain behavior of the bed and indirectly k_{eff}.

Specific thermo-mechanics experiments were planned in recent years to address this. In a blanket, the loading would be internal arising from swelling or differential thermal expansion. However, for simplicity, the initial experiments in this area aimed at reproducing the internally-induced strain by applying an external force on the pebble bed to study its stress/strain behavior and to measure the effect on the effective thermal conductivity (e.g. see Refs. [8, 21, 27, 28, 29, 30]). The experiments aim at investigating the bed behavior over a number of load cycles, including the effect of plastic deformation and creep on the pebble bed strain and the corresponding k_{eff}. Initial results were successful in confirming local plastic deformation at the pebble to pebble contact due to the local stress exceeding the yield strength of the material resulting in an increase in contact area and k_{eff}, and in characterizing the key effect of thermal creep over relatively short time at temperatures expected in a fusion blanket [31, 32].

Some issues arose with earlier such experiments in particular regarding the load transmission through the bed for long beds and the difficulty of accurately characterizing the bed strain and stress and the corresponding contact area increase by a combination of experimental diagnostic and modeling results. However, the more recent better-controlled experiments show useful relationship between bed strain and applied stress including the effect of plastic deformation and indicate a near-linear influence of strain on Be/He bed effective thermal conductivity. The concurrent development of an integrated model would help to better understand the overall pebble bed stress/strain behavior and to estimate the resulting contact area which could be used as input for thermal conductivity modeling.

4. Remaining Issues and Required R&D

Although the more recent experimental results in combination with modeling analysis has helped greatly in understanding the thermomechanical behavior of pebble bed, some key issues remain, including:

- Previous compression experiments have tended to rely on analysis to infer the contact area between particles. For example, Appendix I shows an analysis of the contact area effect on the effective conductivity for a Be/He pebble bed under cyclic operation from Ref. [8]. In addition to measurement of the compressive load on the bed and of the resulting strain and k_{eff}, post-test measurement of the contact radius of pebbles at various bed locations should be carried out for furthering the understanding of its influence on k_{eff} and for model calibration.

- Integrated effect of differential thermal expansion and swelling on pebble bed is 3-dimensional and provide internal loading. Experiments up to now have made use of uni-directional external loading. Plans should be made to perform test on bed subjected to isostatic loading. This could be generated through a system of multi-dimension piston providing isostatic external loading. Experiments could also make use of differential thermal expansion to provide more prototypical internal and isostatic loading.

- Elastic deformation increases the contact area while maintaining the load. Plastic deformation increases the contact area but reduces the load. Further creep relaxation would reduce the load even more as indicated by recent experiments [31, 32]. In that sense, creep would provide some benefit as it might prevent pebble fracture by allowing for local stress relaxation, and increase lifetime of the pebble bed region. However, it can also affect the thermal conductivity of the bed as relaxation occurs with possible particle shift and change in contact area and/or pressure. For blanket application, the particle bed would have to be designed for acceptable performance under beginning-of-life and end-of-life conditions. Thus, thermal creep behavior for both ceramic breeder and Be pebble beds under operating temperature and realistic operating transients need to be better characterized and would need multi-cycle testing at prototypical temperatures.

- At high temperature (>~600°C) radiation can play an important role in the overall heat transfer within packed beds (e.g. see Ref. [7]) and should be considered when estimating the effective thermal conductivity of packed beds. Experimental data are lacking for these high temperature cases and would be required since the operational temperature limits for both Li ceramics (the limit is dependent on the specific Li ceramic) and Be (~700°C) are higher than 600°C.

- In-situ testing of irradiated beds with the possibility of characterizing the stress/strain behavior and measuring the temperature distribution (from which k_{eff} can be estimated) is needed. Laboratory testing of irradiated pebbles is certainly not sufficient since any handling of the pebbles would change the configuration of the bed and the particle to particle contact area. Results from such experiment would be of little value. The pebble bed mock-up should be irradiated at relevant neutron fluence and temperature and its behavior determined through in-situ diagnostics

5. Suggested Strategy

The effort required to address the remaining issues can be considered within an overall strategy. While Figure 1 showed the overall R&D roadmap to address the issue of blanket pebble bed thermomechanical behavior, a more focused strategy can be extracted from it and is summarized in Figure 3. A time line is not included since it would be dependent on the amount of resources, level of effort and priority assigned to this R&D area by the international ceramic blanket community. However, where appropriate some very rough estimate of the time required for certain tasks are included more as a relative comparison of the expected effort.

The modeling and experimental effort are pursued in parallel but with constant input/feedback links with the same ultimate goal of: "providing the ability to predict with required confidence the thermomechanical performance of Li ceramic and Be pebble beds under the complete range of blanket operating conditions."

The initial effort aims at identifying the key parameters affecting the pebble bed thermomechanical behavior through first principles, experiments aimed at understanding separate effects, and model development and application. This has essentially been accomplished.

On the experimental side, the strategy assumes an initial selection of preferred bed characteristics based on input from the earlier experimental results, the modeling effort and also on the fabrication development effort (e.g. see Ref. [33]). Ideally, initial input from in-situ testing of irradiated pebble bed would also be useful at this stage. However, there seems to be some delay on the planning and performance of these irradiation experiments. This selection process is ongoing.

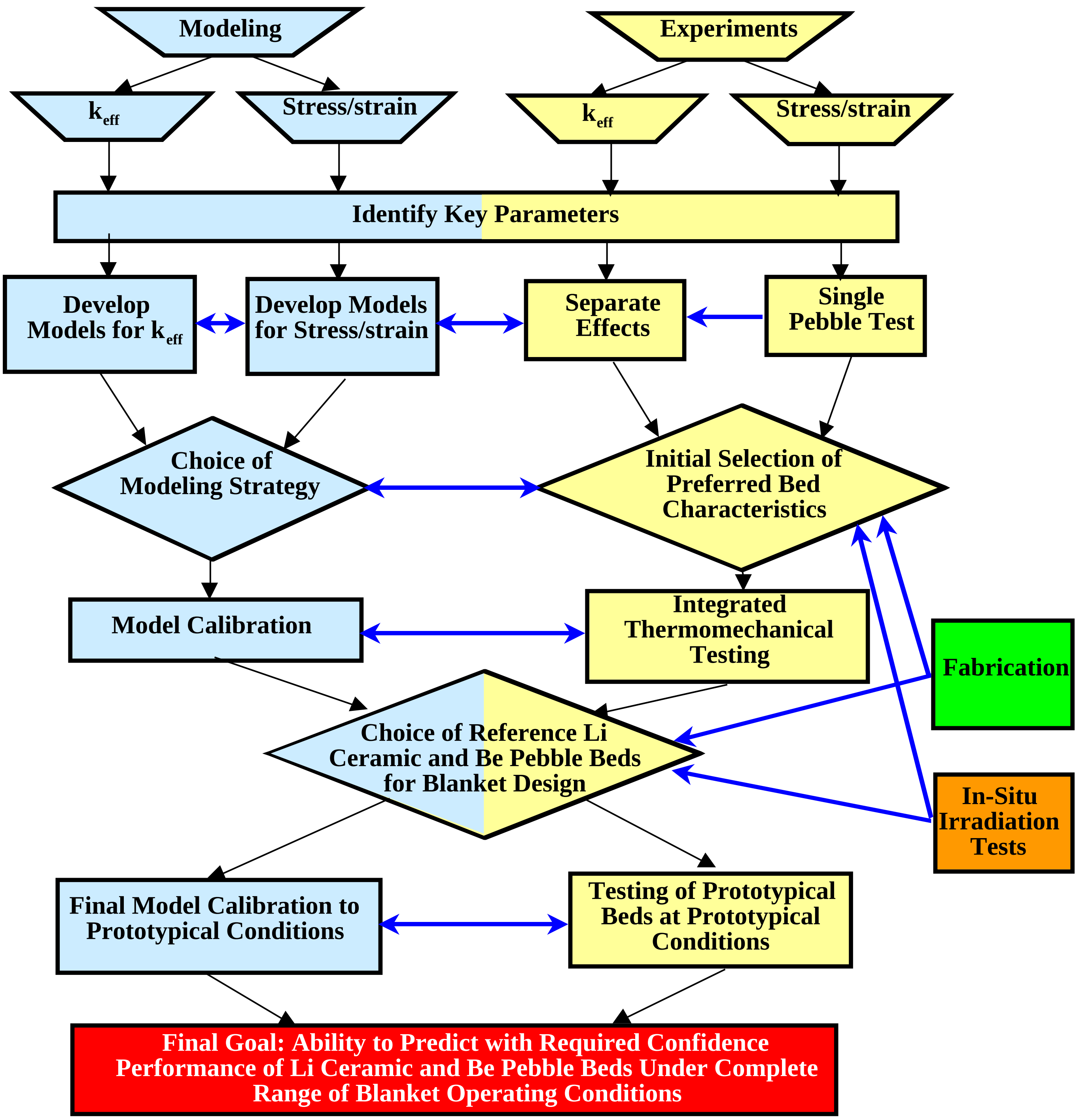

Figure 3 R&D Strategy to Address Li Ceramic Blanket Pebble Bed Thermomechanics Issues

Integrated thermomechanical testing of the selected particle beds would then be carried out over a time frame of about 5 years. In-situ irradiation tests would have to be performed also in parallel. Results from these in combination with input from modeling analysis and fabrication development (feasibility and cost of large scale production and quality of pebbles, would lead to the choice of the reference Li ceramic and Be pebble beds for blanket design.

These prototypical beds would then need to be tested over prototypical conditions. The period required for design, fabrication and testing of these prototypical beds would roughly be 5-10 years.

The modeling effort includes parallel model development based on different approaches. At some point a selection would have to be made as to which model to use for the final extrapolation from prototypical experimental data to the complete range of blanket operating conditions (see Fig. 2).

Two strategies are foreseen:

I. Use a detailed deterministic model for k_{eff} with the right physics to be thoroughly calibrated with prototypical experimental results, and factoring in any departure from the ideal geometry typically assumed in such a model. It is important that the right physics be modeled for the primary processes. For example, for k_{eff} modeling in particular for Be/He bed with a large ratio of k_s/k_g, the contact area plays a key role. The heat flux is then certainly not uni-dimensional and at least a two-dimensional model (or a quasi 2-D model) would be required to correctly account for heat flux convergence at the contact area. A sister stress/strain model is also required, including plastic deformation and creep effects, to characterize the thermomechanical behavior of the bed under different blanket operating and loading conditions and to provide an estimate of the contact area for input to the k_{eff} model. These sister models could be run iteratively at each incremental temporal and spatial steps since k_{eff} would also be required to determine the local temperature and the resulting stress/strain behavior.

II. Adopt a single overall model based on a semi-empirical approach minimizing the number of parameters to be changed by freezing design parameters as much as possible (e.g. pebble size, blanket region dimension, and selected material type) and focusing only on parameters for extrapolation such as temperature and irradiation effect. This model would be evolved directly from calibration with experimental data but would include some physics basis to allow for general extrapolation over a limited range for a few and specific number of parameters (e.g. temperature level, dpa level).

Although the second approach does have merit, including minimizing the resources required for model development and the requirements on experiment in terms of detail parameter definition, the first approach is recommended here for the following reasons:

1. Changing one parameter such as temperature would affect a number of processes which would have to be correctly modeled for the extrapolation to the operating range of

parameters. For example, it is not clear that the effective thermal conductivity would maintain the same trend as observed within the experimental parameter range when extrapolated outside this range since the inter-relation between different processes might result in a different overall trend outside the calibrated range.

2. It is not clear whether the prototypical material can be chosen ahead of time for a full range of experimental data to be obtained for a complete calibration of the simpler semi-empirical models. It is possible that in the future decision on the choice of material might result in different sizes and/or different material types (e.g Li ceramic breeder material or quality of Be material) and different surface characteristics. Thus, all these parameters should be included in the model to help its application for extrapolation. New experimental data would be required anyway but if the model has been calibrated extensively for one kind of model, fewer experimental data would be required with the new material selected just covering some key parameter space, and extrapolation could still be performed with acceptable confidence.

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Appendix I

UNDERSTANDING THE CONTACT AREA EFFECT ON THE EFFECTIVE THERMAL CONDUCTIVITY FOR BE PACKED BED UNDER CYCLIC OPERATION

Introduction

Reimann, et al. [1] have shown some interesting thermomechanical behavior of a compressed 1-mm Be pebble bed. The effective thermal conductivity, k_{eff}, is measured by the hot wire method, which makes use of a long miniature heater embedded in the center of the packed bed. At time, t=0, the electric power is switched on and the temperature increase over time is used to estimate k_{eff}. The experimental set up consists of a cylindrical container with a diameter of 10 cm and a height of 10 cm, which is filled with the Be pebbles and which can be compressed by a piston. Both the stress and strain of the bed are measured as well as k_{eff} for temperatures up to 480°C. The experiment was done by observing the bed thermo-mechanical behavior under increased compression and then under relaxation to zero stress. Typically, during the first compression stage, the bed strain increases with stress, and so does k_{eff}. During the ensuing relaxation phase, as the stress is decreased, the strain still remains high as does k_{eff} until a very low stress level is reached when k_{eff} is seen to decrease appreciably.

It would be interesting to try to understand the processes that might cause this behavior to help to better: understand the thermo-mechanical behavior of Be packed beds; interpret experimental results; and predict the bed behavior in blanket situation.

2. Data Analysis

2.1 Experimental Data at Ambient Temperature

Table 1 summarizes the results for a Be pebble bed at ambient temperature. These data were retrieved from the plotted experimental results shown in Ref. [1] and reproduced in Fig. 1. When the bed is first compressed, the strain increases quite rapidly, indicating the possible re-arrangement of the particles, after which the strain increases linearly with stress up to the maximum imposed level of 6 MPa. During this compression phase, the corresponding values of k_{eff} also increase substantially, by about a factor of 6, indicating the major influence of increasing contact area. When the stress is then relaxed, the corresponding strain decreases only slightly indicating that the deformation caused to increase the contact area was in the plastic regime. Interestingly, the corresponding k_{eff} also does not decrease much until a very low stress is reached when k_{eff} decreases by a factor of 3.

Table 1 Thermo-mechanical parameters for 1-mm Be pebble bed with porosity of 39% at ambient temperature [1]

Measured uniaxial strain (%)	Measured uniaxial stress (MPa)	Measured k_{eff} (W/m-K)	Contact radius estimated from yield stress, r_c (μm)	Strain estimated from r_c (%)
0	0	1.4	0	0
0.3	0.8	3.3	31	0.2
0.48	2	4.6	50	0.5
0.68	3.7	6.7	68	0.93
0.69	3.8	6.8	69	0.96
0.88	5.6	8.7	83	1.39
0.91	5.8	9.7	85	1.46
0.9	3.8	9		
0.89	2	8.9		
0.82	0.5	8.1		
0.72	0	3.3		

Since the contact area (of radius, r_c) is known to play a key role in determining k_{eff} for a pebble bed in particular for high ratio of solid to gas conductivity (k_s/k_g) [e.g. 2,3], it would be interesting to try to understand the relationship between stress, strain and contact area.

2.2 Pebble Bed Geometry

A single-size pebble bed configuration is mostly orthorhombic, as illustrated in Fig. 2 [4]. This means that in one plane the pebble can be considered as being arranged in a single row formation with, while in the next plane nested pebbles would be arranged in a triangular fashion. For simplicity, to try to better understand the geometric effect, it is assumed here that the pebbles are arranged in a single row formation. Results in the end would have to be slightly modified to account for the exact overall configuration.

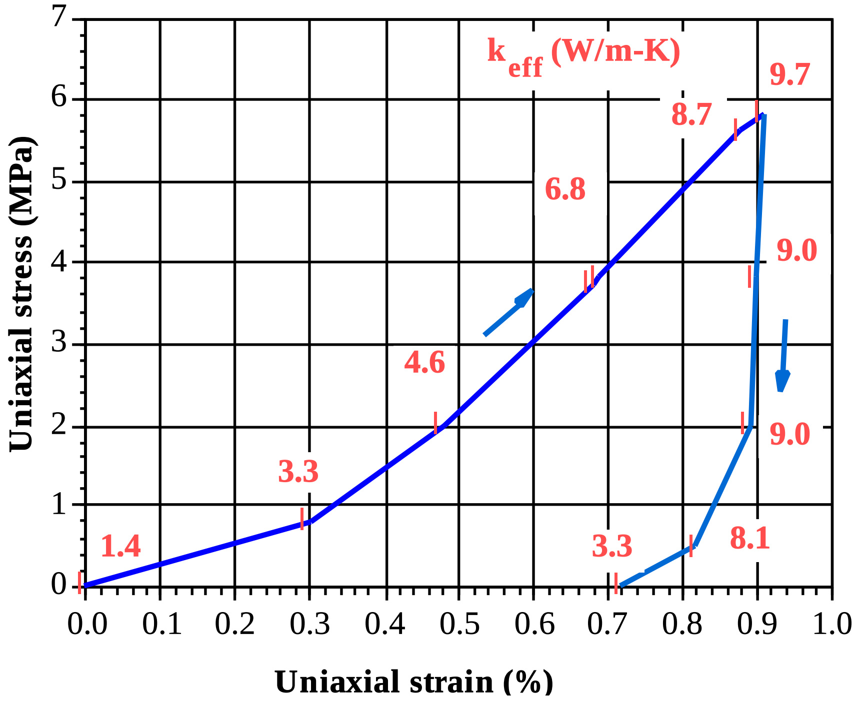


Figure 1 Thermo-mechanical behavior of 1-mm Be pebble bed with porosity of 0.39 at ambient temperature [1]

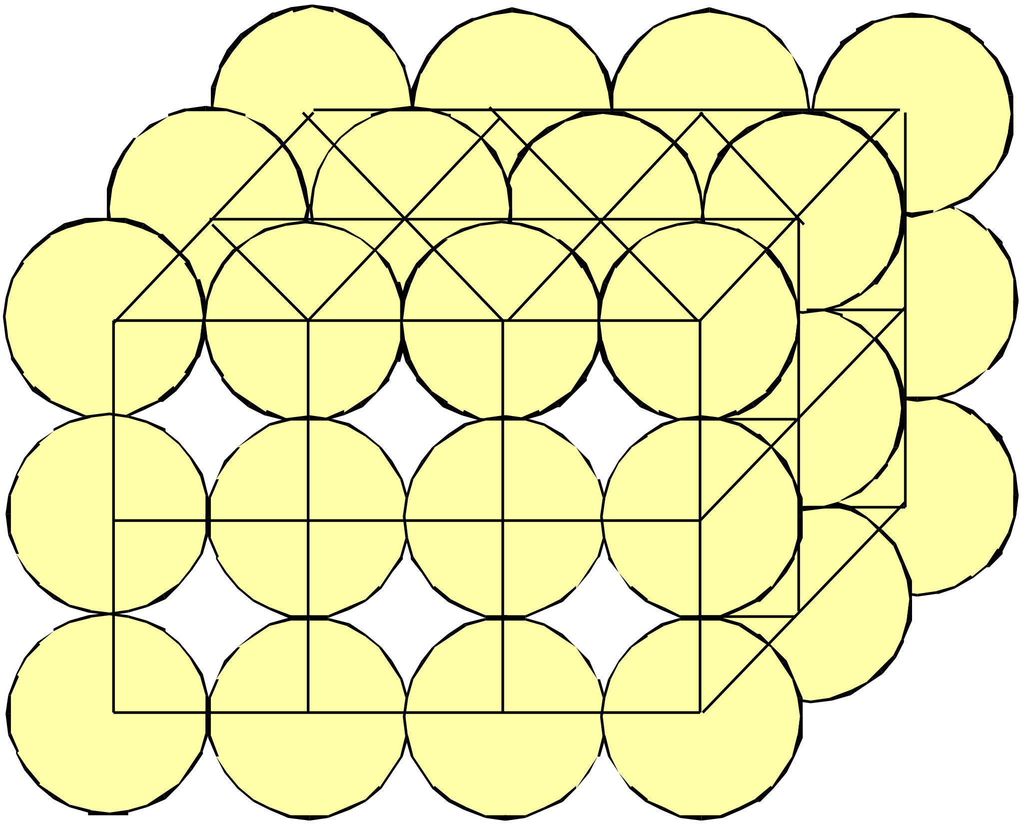
Figure 3 shows a unit cell consisting of a single pebble (assumed spherical) from a row of vertically stacked pebbles. Under compression, a pressure, P_{uc}, is applied to the unit cell. This pressure results first in elastic deformation at the point of contact and then in plastic deformation when the yield stress is exceeded locally.

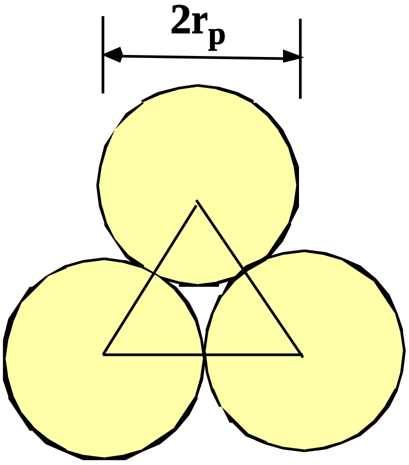
The pebble could be considered as part of a 3-D cylindrical unit cell of length equal to the diameter of the pebble ($2r_p$) and of radius, r_{uc}. r_{uc} might be slightly different from r_p as it is set to compensate for any departure from the idealized porosity of this simple geometry, and to reproduce the actual overall porosity of the bed, φ.

$$\phi = 1 - \frac{2r_p^2}{3r_{uc}^2} \qquad (1)$$

(e.g. for φ=0.39 and r_p=0.5 mm, r_{uc}=0.523 mm)

Orthorhombic Packing





$$(1-\phi)=\mathbf{0.5\pi/3sin60}$$

$$\phi=\mathbf{0.3954}$$

Figure 2 Orthorhombic packing of pebble bed

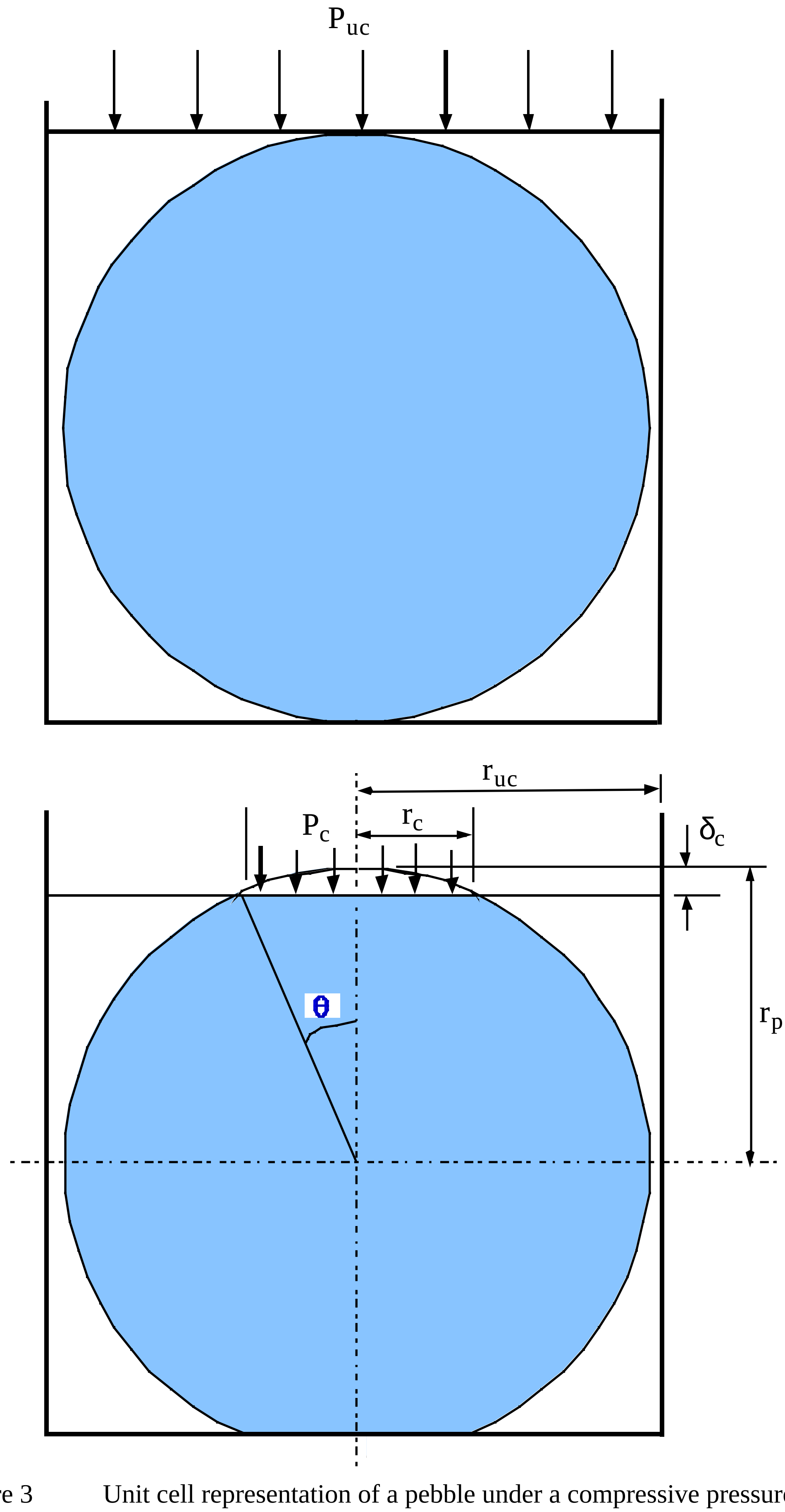


Figure 3 Unit cell representation of a pebble under a compressive pressure, P_{uc}.

Under the compressive stress, P_{uc}, the particle deforms by an increment δ_c over a bed length corresponding to r_p, resulting in a strain, ε:

$$\varepsilon = \frac{\delta_c}{r_p} \qquad (2)$$

The pressure at the contact region can be estimated from the pressure on the unit cell by considering the respective pressure-transmitting areas:

$$P_c = P_{uc} \frac{r_{uc}^2}{r_c^2} \qquad (3)$$

This is particularly applicable under yield conditions where the contact radius, r_c can be estimated by setting the local contact pressure equal to the yield stress, σ_y, of the material [5].

The corresponding unit cell displacement ($2\delta_c$ per pebble diameter) can be estimated from geometry consideration as a function of angle θ.

$$\delta_c = r_p(1 - \cos\theta) \qquad (4)$$

where θ can be estimated from the contact radius:

$$\sin\theta = \frac{r_c}{r_p} \qquad (5)$$

From the results shown in Table 1, the contact radius can be estimated from the uniaxial stress (equivalent to P_{uc}) by using eq. (3) and equating the contact pressure P_c to the yield stress of Be (assumed to be 220 MPa at ambient temperature[6]). The resulting contact radii from these estimates are also shown in Table 1, the maximum estimated r_c being 85 μm at the maximum uniaxial stress of 5.8 MPa.

From the estimated r_c, the bed displacement can be calculated from eqs. (4) and (5), and the corresponding strain estimated from eq. (2). This estimated strain is also shown in Table 1 and can be compared with the measured strain to obtain some judgement on the validity of this simple geometric model. The estimated strain is lower than the measured strain at low stress level and increases faster with increasing stress to be higher than the measured strain at high stress levels. Overall, the largest difference is within about 50 or 60% which is quite encouraging given the simplicity of the model and the probable need for fine-tuning the results to account for the actual overall bed geometric configuration.

2.3 Effective Thermal Conductivity Modeling

It would be interesting to use these r_c values in a k_{eff} model to estimate k_{eff} for the different cases shown in Table 1 and to compare them with the measured values. However, in order to do this a model which correctly accounts for the effect of contact area must be chosen. The SZB model [3] is an example of a model where the effect of contact area is factored in and could be used to shed some light on the results. However, a model which better accounts for the 2-D heat flow path seen in a pebble bed would probably provide a better tool for such an analysis or at least a good confirmation of the results. For example, a model based on a unit cell approach has been used before [e.g. 2, 7]. Ref. [2] shows a more recent development of such a model for particular use with bed with high k_s/k_g ratio such as for Be and He. This model utilizes a unit cell, similarly to the model shown in Fig. 1, but based on a quarter of a pebble from symmetry considerations. Figure 4 shows the basic unit cell including the inclusion of the contact area effect. Uniform temperatures are imposed at the upper and lower boundaries (T_{high} and T_{low}) and the side boundaries are adiabatic. The 2-D heat conduction equation is solved for the unit cell including the effect of gas conduction in the Knudsen regime (Smolokovski effect) for regions close to the contact area, which is an important process which must be included. The total heat flux to the unit cell, Q_{uc}, is then estimated by integrating the local heat flux at the upper or lower boundary (they should be equal based on conservation of energy).The bed k_{eff} can then be estimated as follows:

$$Q_{uc} = k_{eff}\,(T_{high} - T_{low})\frac{\pi r_{uc}^2}{r_p} \tag{6}$$

It seems clear from past analysis and from these experimental results that the contact area is the primary factor influencing the bed conductivity. It is recommended that the SZB model as well as the above unit cell model (being evolved at FZK[8]) be used to further the understanding of the thermo-mechanical behavior of the packed bed and in particular of the estimated contact area effect. In parallel, it would be very interesting to observe under a microscope the indentation in selected pebbles (at various locations) to estimate the size of the contact areas and the average number of contact areas per pebble. These could be done on Al pebbles to start with as they are easier to handle. Pebbles from experiments with different maximum loadings can be used to understand the effect on the size of the contact area and to guide the modeling activity.

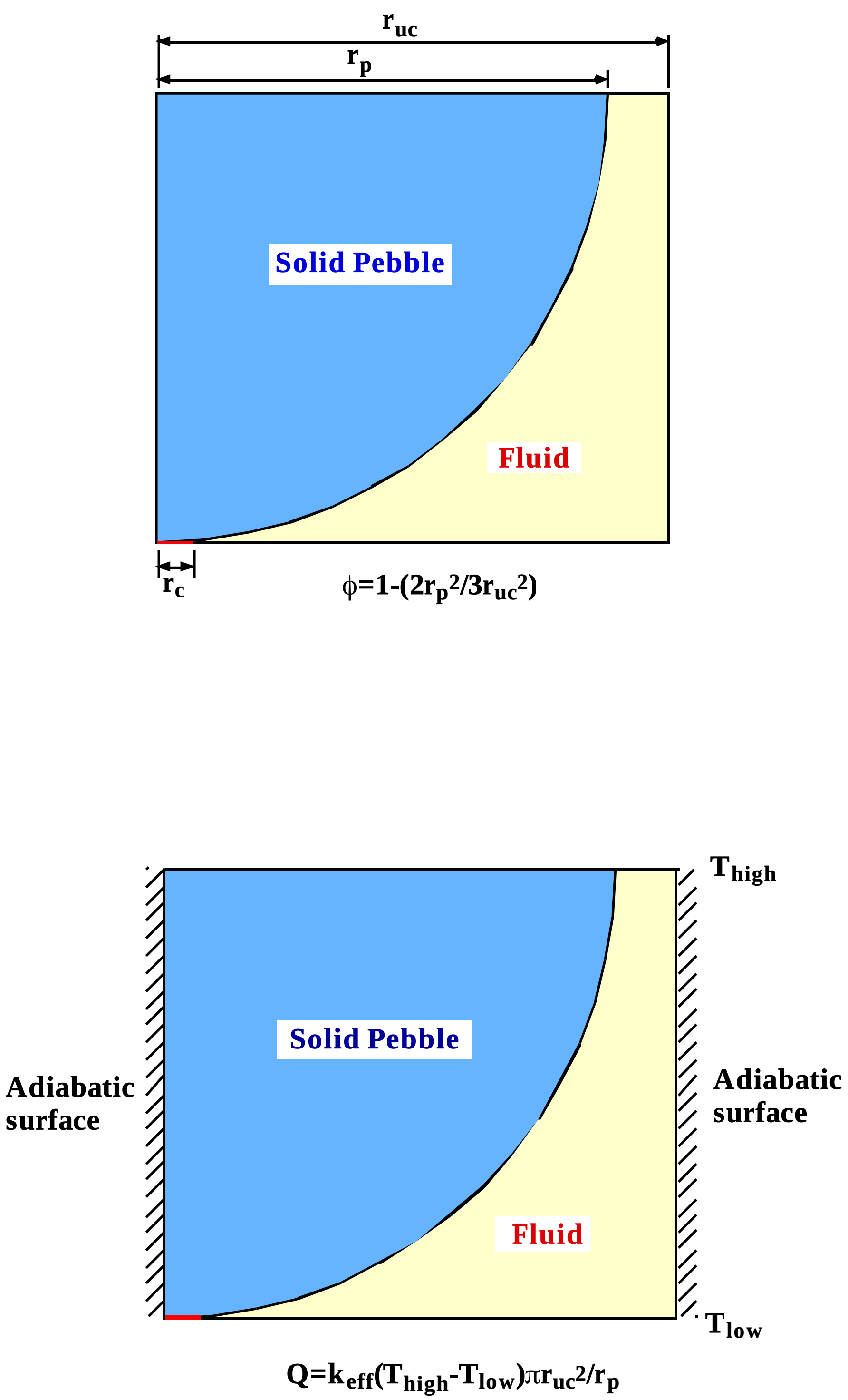


Figure 4 Unit cell geometry for 2-D k_{eff} model

2.4 <u>Contact Conductance Effect</u>

As the pebble bed compressive load is relaxed, the size of the pebble contact area formed under yielding or plastic deformation would remain the same. The only change is a decrease in the pressure at the contact. This tends to be a secondary effect when compared to the contact area effect but worth analyzing to help in better understanding the overall loading and relaxation behavior of the bed.

Contact to contact conductance has been studied before by many researchers and models have been evolved. For example, Ref. [9] shows the analysis results for Be in contact with steel based on two different models (Shlykov et al., and Lemczyk &Yovanovich). In addition to the pressure at the contact, key parameters are the hardness of the material (or the ultimate strength) and the surface characteristics (represented by the roughness). At low pressure the roughness would create gaps which would increase the contact resistance whereas at higher pressure the gap is reduced and the contact conductance is increased. Figure 5 reproduces a set of results from Ref. [9]. It shows the contact conductance as a function of the ratio of contact pressure to surface hardness for different surface roughnesses. Interestingly, the contact conductance remains at a low value as the contact pressure to hardness ratio is increased until at some level of contact pressure to hardness ratio it starts increasing sharply. This kind of threshold at which this sharp increase in conductance occurs is dependent on the roughness of the surface, seemingly occurring earlier and more sharply for low roughnesses.

One hypothesis regarding the behavior of the pebble bed under loading and relaxation (shown in Table 1 and Figure 1) is that k_{eff} increases with uniaxial stress as the contact area is increased through plastic deformation (causing an increase in strain). When the load is relaxed the contact area remains the same but the pressure at the contact decreases until at low enough stress the pressure at the contact is such that the resistance induced at the contact starts affecting the overall bed thermal conductivity which, in turn, is reduced. To test this hypothesis, it would be interesting to estimate the contact pressure at which the drop in k_{eff} occurs at the end of the relaxation phase and verify the behavior of the corresponding contact conductance from Fig. 5.

From the results shown in Fig. 1 and Table 1, at the end of the relaxation phase, k_{eff} decreases to 8.1 to 3.3 W/m-K at a uniaxial stress between about 0.1 and 0.5 MPa. The contact radius at this point is the same as that obtained by plastic deformation at the highest load, which, from the simple estimate shown in Table 1, is about 85 μm. For r_{uc}=0.533 and an assumed uniaxial stress of 0.3 MPa, the corresponding contact pressure is 11.7 MPa. In the absence of available data on the hardness of Be, it is assumed to be about 3 times the ultimate strength (3x~320 MPa for Be at ambient temperature). The contact pressure to hardness ratio is then 0.012. From Fig. 5, it is interesting to note that this at the point where the contact conductance starts its sharp increase for the low roughness case (1 μm). It is reasonable to expect this increase to occur at lower contact to pressure ratio and probably in a sharper manner for even lower roughnesses. This lends some credence to the hypothesis that the decrease in k_{eff} observed at the end of the relaxation phase might be due to an appreciable decrease in the contact conductance as the stress is lowered.

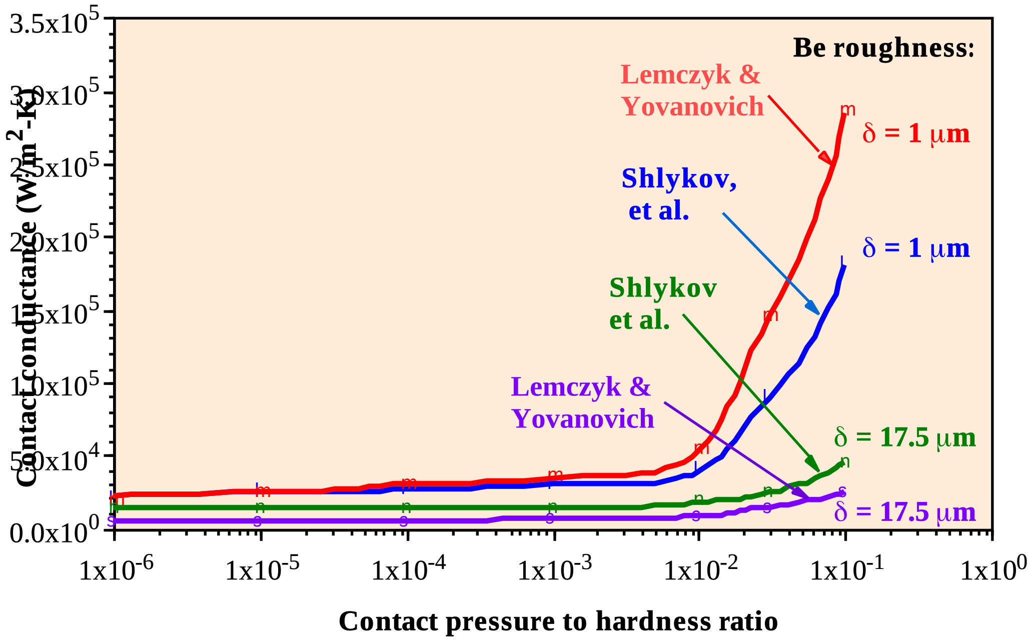


Figure 5 Contact conductance at a Be/steel surface as a function of the contact pressure to hardness ratio for different surface roughnesses (from Ref. [9])

2.5 <u>Experimental Data at Higher Temperature</u>

Ref. [1] also shows results for the Be/He pebble bed at 475°C. These are summarized in Table 2. A similar analysis as that shown in Section 2.2 for the ambient temperature case was performed. The contact radii calculated from the corresponding uniaxial stresses are shown in Table 2, as well as the associated strain values estimated from the contact radii. The yield stress for Be was assumed to be 160 MPa at this temperature [6]. The maximum contact radius is 96 μm corresponding to an uniaxial stress of 5.4 MPa. Again, the calculated strain values are of the same order as the measured ones, being very close at lower stresses and higher by about 50% at the maximum stress.

Table 2 Thermo-mechanical parameters for 1-mm Be pebble bed with porosity of 39% at 475°C [1]

Measured uniaxial strain (%)	Measured uniaxial stress (MPa)	Measured k_{eff} (W/m-K)	Contact radius estimated from yield stress, r_c (μm)	Strain estimated from r_c (%)

0	0	2.3	0	0
0.1	0.2	3.4	19	0.07
0.44	1.3	5.1	47	0.44
0.63	2.3	5.9	63	0.79
0.85	3.5	8.5	77	1.20
1.0	4.8	9.3	91	1.65
1.2	5.4	11.3	96	1.86

A contact conductance estimate was also done for this case for the maximum contact radius. For this case, it is not clear from Ref. [1] at which stress level k_{eff} decreases substantially (at the end of the relaxation period). Assuming this occurs at about 0.1 MPa, the corresponding contact pressure is about 3 MPa. The ultimate strength of Be is about 220 MPa at 475°C [6], and the hardness is assumed to be about 3 times that value. The corresponding ratio of contact pressure to hardness is about 0.005. From Fig. 5, again this is close to when the contact conductance starts increasing appreciably in particular for cases with roughnesses of ~ 1μm or less.

2.6 New Experimental Data for Contact Area of Compressed Al/He Pebble Bed

Following discussion at FZK, a test case was run by compressing a bed of 2-mm Al with He gas and measuring the stress/strain behavior up to a maximum uniaxial stress of 7.3 MPa [10]. Selected pebbles were then retrieved and observed under a microscope to better judge and assess the shape, size and surface characteristic of the contact areas. The preliminary examinations show the presence of several indentations on the pebble indicating the locations of the contact regions. The contact area is appreciable in particular for the pebbles next to the piston. For the other pebbles, the contact diameter is very roughly estimated at about 0.1 mm using the modest magnification provided by the available microscope. Examinations using better more powerful microscopes are being planned and will help shed light on this. Also, the exact properties of the Al used for the pebble are required (in particular the yield stress) to estimate the contact radius under the given load. It is planned to do this and to compare the results with the observations under the microscope.

3. Conclusions

- The thermo-mechanical behavior of a Be packed bed under loading and relaxation conditions experimentally determined in Ref. [1] was further assessed.

- The experimental results show that when the bed is first compressed the strain increases quite rapidly, indicating the possible re-arrangement of the particles, after which the strain increases linearly with stress up to the maximum imposed level. During this compression phase, the corresponding values of k_{eff} also increase substantially, indicating the major influence of increasing contact area. When the stress is then relaxed, the corresponding strain decreases only slightly indicating that the deformation caused to increase the contact area was in the plastic regime. Interestingly, the corresponding k_{eff} also does not decrease much until a very low stress is reached when k_{eff} decreases appreciably.

- A simple geometric model was used to estimate the contact radius corresponding to a given stress level based on the yield stress of Be and the corresponding strain level. The maximum contact radius was 85 and 96 μm for the cases at ambient temperature and 475°C, respectively (corresponding to maximum uniaxial stresses of 5.8 and 5.4 MPa, respectively). In general, the corresponding strain levels were quite close to the measured values at low stress levels but higher (by about 50%) than the measured values at the higher stress levels. This is encouraging given the simplicity of the model used and the assumptions regarding the pebble bed configuration.

- One hypothesis regarding the behavior of the pebble bed under loading and relaxation (shown in Table 1 and Figure 1) is that k_{eff} increases with uniaxial stress as the contact area is increased through plastic deformation (causing an increase in strain). When the load is relaxed the contact area remains the same but the pressure at the contact decreases until at low enough stress the pressure at the contact is such that the resistance induced at the contact starts affecting the overall bed thermal conductivity which, in turn, is reduced. This hypothesis was tested by considering the variation of contact conductance with contact pressure.

- Contact to contact conductance has been studied before by many researchers and models have been evolved. In addition to the pressure at the contact, key parameters are the hardness of the material (or the ultimate strength) and the surface characteristics (represented by the roughness). Results from models from Shlykov et al., and Lemczyk &Yovanovich for Be in contact with steel were obtained from Ref. [9] and used in the assessment. Interestingly, the contact conductance remains at a low value as the contact pressure to hardness ratio is increased until at some level of contact pressure to hardness ratio it starts increasing sharply. This kind of threshold at which this sharp increase in conductance occurs is dependent on the roughness of the surface, seemingly occurring earlier and more sharply for low roughnesses.

- For the Be/He pebble bed, for the ambient temperature and 475°C cases, estimates of the ratio of contact pressure to hardness indicate that the sudden decrease in k_{eff} at the end of the relaxation phase seems to occur in the parameter space when the contact conductance decreases appreciably. This adds credence to the contact conductance effect hypothesis, and suggests that although the contact conductance would play a secondary role when compared to the overall contact area effect on k_{eff}, it should still be considered in certain situations.

- It would be very interesting to apply a model to evaluate the k_{eff} of the Be/He pebble bed for the contact radius values estimated here. The SZB model[3] in which the effect of contact area is factored in could be used to shed some light on the results. In addition, a model which accurately accounts for the 2-D heat flow path seen in a pebble bed (such as the one used in Ref. [2]) would provide a very good tool for such an analysis. Such a model is being evolved at FZK and it is recommended that it be used to analyze the contact area effect in relation to the experimental results of Ref. [1]. It can also model the effect of contact conductance and would help to parametrically determine its effect for different assumed loading scenarios.

- In parallel, it would be very interesting to observe under a microscope the indentation in selected pebbles (at various locations) to estimate the size of the contact areas, the average number of contact areas per pebble and the contact area surface characteristics. Contact area is a key parameter in determining k_{eff} and has been estimated based on model fit but apparently not yet accurately characterized through experimental observation and measurement. These could be done initially with Al pebbles (as they are easier to handle than Be pebbles) and would cover test runs at various stress levels. Data from these measurements would be very precious in applying to modeling analysis, in regard to both the size of the contact area and the smoothness of the contact area which can influence the contact conductance.

- Preliminary examinations of 2-mm Al pebbles following a stress/strain experiment with a maximum uniaxial stress of 7.3 MPa show the presence of several indentations on the pebble indicating the locations of the contact regions. The contact diameter was appreciable, very roughly estimated at about 0.1 mm using the modest magnification provided by the available microscope. Examinations using better more powerful microscopes are being planned and will help shed light on this.

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