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Untersuchung des thermohydraulischen Verhaltens der Ermüdungsproben im IFMIF-Mittelflussmodul

Zusammenfassung

IFMIF (International Fusion Materials Irradiation Facility) ist eine in der Planung befindliche Einrichtung zur Bestrahlung von Fusionsreaktor-relevanten Materialien. Das Bestrahlungsvolumen gliedert sich in drei Bereiche, den Hoch-, Mittel- und Niederflusstestmodul.

Das Mittelflusstestmodul (MFTM) besteht aus drei Submodulen, die in Strahlrichtung hintereinander angeordnet sind. Im ersten Submodul auf der Strahleintrittsseite sind drei Ermüdungsproben untergebracht. Zur Einstellung und Konstanthaltung der gewünschten Bestrahlungstemperatur ist eine elektrische Direktbeheizung der Proben vorgesehen. Bei der Auslegung des Submoduls mit den Ermüdungsproben ist insbesondere das Problem zu lösen, wie die gewünschte Bestrahlungstemperatur von maximal 650°C bei möglichst geringen Temperaturdifferenzen in der Probe erreicht werden kann.

Die vorherigen Abschätzungen liefern keine Aussagen über die Temperaturverteilung in der Probe. Hierzu wurden eine Reihe von Simulationsrechnungen unter Verwendung des CFD-Codes STAR-CD durchgeführt. Um den Aufwand in der jetzigen Frühphase der Auslegung gering zu halten, wurden das Modell und die Randbedingungen so einfach wie möglich gewählt. Dennoch liefern die Ergebnisse einen wichtigen Beitrag zu den weiteren Entwurfs- und Auslegungsarbeiten des Konzepts. Die wichtigsten Schlussfolgerungen und Empfehlungen für die untersuchten Konzepte wurden am Ende des Berichts zusammengefasst.

Abstract

IFMIF (International Fusion Materials Irradiation Facility) is a facility under development to irradiate fusion relevant materials. The irradiation volume is divided into three sections, the high-, medium, and low flux test module.

The medium flux test module (MFTM) consists of three submodules arranged in series in the direction of the beam. The first submodule at the beam entrance side is housing several creep-fatigue specimens. Direct electrical heating is envisaged to adjust and control the desired irradiation temperature of the specimens. The main problem in designing this submodule is to reach the level of the irradiation temperature with reasonably low temperature differences in the specimens.

Preliminary estimates confirmed the suitability of the envisaged design for reaching the desired irradiation temperature but did not deliver the temperature distribution in the specimens. To obtain information on this subject a series of numerical analyses was carried out using the CFD code STAR-CD. To keep the effort in the present early design phase reasonably low, the computer model of the test installation including the initial and boundary conditions were kept as simple as possible. Nevertheless, the results are a useful additional contribution to the further design and layout of the concept. The most important conclusions and recommendation on the concept variants are summarized at the end of the report.

Content

1. Introduction

IFMIF (International Fusion Materials Irradiation Facility) is a facility under development to irradiate fusion relevant materials, in particular steels. The irradiation volume is divided into three sections, the high-, medium, and low flux test module. Whereas it is intended to irradiate a large number of non-instrumented steel specimens in the high flux test module, the medium flux test module (MFTM) serves mainly to test a small number of instrumented creep-fatigue specimens at temperatures between 250 and 650 °C. The tubular specimens with a length of about 35 mm should be kept at an almost constant temperature independently of the operational conditions of the source of radiation. This requires - besides of the cooling of the inner surface – adequate electrical heating of the specimens. The equipment for cooling and in particular heating is crucial for the space requirement inside the submodule. This means that the heating and cooling concept should be basically defined before the design of the submodule including the optimum use of the available space will be further elaborated. With this regard the present preliminary thermal-hydraulic analysis of the creep-fatigue specimens delivers a useful contribution to the further development of the MFTM.

2. Actual concept of the submodule

The present concept of the MFTM is shown in Fig. 1 [1]. It consists of three submodules arranged in series in the direction of the beam. The first submodule at the beam entrance side is housing three creep-fatigue specimens. The third submodule is envisaged for the irradiation of breeding materials. Between these two ones another submodule is placed containing a Tungsten moderator. To assure the mechanical stability in the two directions perpendicular to the beam the submodules are designed as frame construction. In the third direction the submodules are supporting each other. To improve the neutron economy the whole assembly of submodules is surrounded by Graphite reflectors.

Fig. 2 shows the design of the submodule with the creep-fatigue specimens. The concept of the support, the cooling and the loading of the specimens is based on experience obtained in related experiments in the Dual Beam Facility at the Zyklotron of Forschungszentrum Karlsruhe [2]. The adaptation of that concept to the present

MFTM conditions is shown in Fig. 3. The tubular specimen (inner diameter 8 mm; wall thickness 0.5 mm; length 38 mm) with its threaded ends is joined to the loading device by an adapter and a screw cap. The cooling of the specimen is accomplished via the inner surface. The helium coolant enters the device sidewise at the top end and is released at the bottom end into the frame (latter not shown in Fig. 3). The load is applied by a linear motor arranged above the upper traverse of the frame. A load cell serves to measure the applied force.

Direct electrical heating is intended to adjust and control the temperature of the specimens. This requires electrical isolation of the specimens including the power connections against the remainder of the submodule. This is achieved by isolating discs which must additionally be leak tight. The necessary clamping forces are applied by electrically isolated bolts and nuts.

3. Preliminary estimates

Main problem in designing the submodule with the creep-fatigue specimens is to achieve the desired irradiation temperature of maximum 650 °C with a temperature variance in the specimens as low as possible. At the first glance it seems to be reasonable to take profit of the nuclear power generated in the specimens to generate the desired temperature difference between specimens and coolant. However, because of the small wall thickness of the specimens the maximum heat flux amounts to only 0.5 W/cm^2. Hence, for reaching 650 °C the heat transfer coefficient should be as low as 0.001 to 0.002 W/cm^{2}K which would necessitate very low helium mass flow rates with the consequence of large helium temperature rises because of the nuclear power generated in the massive supports of the specimens. On the other hand, as electrical heating of the specimens is necessary in any case to maintain the temperature in the case of beam interruptions, it seems to be reasonable to use this system to control the temperature in general.

For a first estimate of the necessary heating and cooling conditions helium velocities of 100 to 500 m/s at a pressure of 2 bar and a temperature of 25°C were assumed. The nuclear power in the supports of the specimens amount to about 520 W. Because of the cross section relations the electrical power generation is concentrated in the thin-walled section of the specimen; the electrical power density in the remainder is negligible. The estimate shows that a specimen temperature of 650°C can be reached under the following conditions:

Helium mass flow rate	1.6 to 8.1 g/s
Heat transfer coefficient	0.04 to 0.16 W/cm^2K
Electrical power	183 to 742 W
Heat flux (electr.)	9 to 37 W/cm^2
Helium temperature rise	85 to 30 K

Furthermore, the results confirm the expectation that the contribution of the nuclear power to the specimen temperature is rather small (12 to 3 K).
The electrical resistance of the specimen is small: Using the electrical conductivity of the martensitic steel MANET at 200°C (1.35 m/Ω mm2) one obtains a value of 1.66·10-3 Ω. This yields maximum values of current and voltage of 667 A and 1.11 V, respectively.
A maximum force of 10 kN has been suggested for the load cell which corresponds to an axial main stress in the specimen of 750 MPa. This is sufficient for the expected stress range of the steel to be investigated. Assuming for the rotating/sliding shaft a thread of M10x1 and a friction coefficient of $\mu = 0.15$ one obtains a motor torque of about 10 Nm. A suitable linear motor would be Type PL50-RDM 596/50B with gear 1:10 produced by Berger Company. It has a length of 200 mm and flange dimensions of 85x85 mm. These dimensions are slightly above those of the motor shown in Fig. 3.
In summary, the estimates described above have shown that the envisaged concept is reasonable with respect to cooling, heating, and mechanical loading of the specimens.

4. Thermal-hydraulic analyses

The estimates described in the previous section do not yield information on the temperature distribution in the specimens. With respect to this question a series of thermal-hydraulic simulations was carried out using the CFD-Code STAR-CD. To keep the effort in the present early design phase reasonably low, the computer model of the test installation including the initial and boundary conditions were simplified as far as possible. Nevertheless, the results are a useful additional contribution to the further design and layout of the concept.

4.1 Model used in the simulations

Fig. 4 shows the axial-symmetrical model used in the simulations. The model is restricted to the upper half of the test section. Strictly speaking this is correct only in the case of axial symmetry which is not the case in the present application because of the helium temperature rise between the inlet and the outlet. However, as the temperature of the specimen is much larger than the temperature of the helium, the axial temperature profile of the specimen is not far from being symmetrical. Hence, the applied simplification is considered to be reasonable in the early phase of the design. Furthermore, the radial helium inlet at the upper end of the test device was not modelled because it is not relevant for the temperature distribution in the specimen. Coolant flow inside the central channel of the device including the specimen is vertically from top to bottom.

The standard High-Re-Number k-ε turbulence model is chosen for subsequent analysis. The model includes 2850 fluid elements, 11 elements are assigned in the radial direction with the first node at $y^+ \cong 30$. Since the thin wall of the specimen (0.5 mm) enables to ignore the temperature gradient in the radial direction, only one layer of solid elements was used for the representation of the specimen.

4.2 Initial and boundary conditions

The boundary conditions of the helium cooling were prescribed at the inlet of the model. For most cases, the following values were applied: coolant velocity at the model inlet 77.7 m/s (about 300 m/s inside the specimen), temperature 50 °C, pressure 2 bar. These conditions correspond to about the average of the range assumed in Sect. 3. In some preliminary analyses the helium velocity was varied to elucidate the role of this parameter for the temperature distribution. Adiabatic conditions were assumed for all boundaries except the helium cooled surfaces.

The nuclear analyses of the MFTM are not yet completed. Therefore, the nuclear power density distribution needed in the thermal-hydraulic analyses was approximately determined by extrapolating the distribution available for the High Flux Test Module taking additionally into account more actual results of S. P. Simakov [4] und P. Vladimirov [5]. The extrapolated results for the axis of the specimen (x = 0; z = 9 cm) are shown in Fig. 5. They refer to steel with a density of 7.8 g/cm^3. The maximum value in the centre of the beam amounts to 10 W/cm^3. The vertical distribution (y-axis) was taken into account in the simulations. The variations in the two other directions were neglected.

With respect to the electrical heating a power density in the thin-walled part of the specimens of 1200 W/cm^3 was assumed. The electrical power generation in the massive support parts of the device was ignored.

With respect to the material data of the steel the usual properties of ferritic-martensitic steels were used. Data of other materials as well as the concepts variants investigated are described in the section below.

4.3 Results

Already in the initial phase of the analyses it became evident that significant temperature differences exist in the axial direction of the specimens. Therefore, it was investigated in a first step whether these difference can be reduced by varying the coolant velocity. To that the inlet velocity was reduced stepwise from initially 77.7 m/s to 10 m/s. The results showed that the maximum specimen temperature of 650 °C can be kept constant by adjusting in parallel the electrical power. However, a significant reduction the temperature differences was not achieved.

In all subsequent cases the same electrical power density (1200 W/cm^3) and coolant inlet velocity (77.7 m/s) was applied, i.e. each variation of the other parameters led to another maximum specimen temperature. To allow, nevertheless, the valuation of the temperature constancy of the specimens a relative unit $L_{5\%}$ was introduced which is defined as follows: $L_{5\%}$ is the relative (i.e. related to the total) length of the specimen which has a temperature variation of less than 5 % (related to the difference between the maximum specimen temperature and the coolant inlet temperature). Hence, the related absolute temperature difference depends on the maximum specimen temperature, and amounts e.g. 10 K at 250°C and 30 K at 650°C.

Table 1 gives an overview on the parameter variations and the results obtained.

Table 1: Parameter variations and results of the thermal-hydraulic simulations using the CFD code STAR-CD

Case	1	2	3	4	5	6	7	8
$q_{el,spec.}$ (W/cm^3)	1200	1200	1200	1200	1200	1200	1200	1200
q_{nucl}	Fig. 5	-	Fig. 5	Fig. 5	-	Fig. 5	Fig. 5	-
Adapter-Mat.	SS	SS	Cer	SS	SS	Cer	SS	SS
$Q_{s.c.}$ (W/cm^3)	-	-	-	20	20	-	-	-
$Q_{thr.}$ (W/cm^3)	-	-	-	-	-	170	-	-
He-guide tube	-	-	-	-	-	-	with	with
$T_{max,spec.}$(°C)	549	442	540	562	483	586	499	440
$L_{5\%}$	0,46	0,38	0,43	0,48	0,37	0,83	0,52	0,42
Fig. No.	6	7				9	10	11

Fig. 6 shows the calculated temperature distribution for the reference concept with nuclear power generation (Case 1), on top of the figure for the entire model, on bottom for the specimen only. The maximum temperature in the specimen amounts to 549°C, whereas the minimum temperature at the upper end is only 424°C. $L_{5\%}$ achieves a value of 0.46, i.e. on a fraction of 46 % of the specimen length the specimen temperature is between 95 und 100% of the difference against the helium inlet temperature. In the transition region between the specimen and the specimen support the temperatures are between 350 und 450 °C.

Fig 7 shows the results for the reference design but without nuclear power generation (Case 2). The maximum specimen temperature is now about 110 °C less than before with nuclear power. This means that to keep the specimen temperature constant the electrical power must be increased significantly when the beam is switched off. In the support region the loss of power causes a drop of the temperature to almost the level of the helium temperature. This increases the heat flux from the specimen into the support region with the consequence that the temperature difference in the specimen becomes larger and $L_{5\%}$ becomes less than in Case 1 with nuclear power.

Starting from reference case 1, several design variants were investigated subsequently with the objective to reduce the temperature differences in the specimens. In principle, the following measures seem possible: Arrangement of a thermal isolator between the specimen and the support, additional electrical heating or reduction of the cooling of the transition region between specimen and support. A technically feasible solution to increase the thermal isolation is to use for the adapter (see Fig. 3) a material with a low thermal conductivity, e.g. a ceramic. Calculations with an adapter made of Al_2O_3 did not yield the desired result (Case 3). On the contrary, as the isolating adapter hinders the heat flux from the screw cap to the inner surface, the temperature distribution is even more unfavourable (see Table 1).

Electrical heating of the outer surface of the screw cap seems technically feasible. Such a solution was simulated by adding internal heat sources to a ring of cells close to the outer surface (see top of Fig. 8). A heat source density of 20 W/cm^3 was chosen according to a heat flux of 4 W/cm^2. The results of the calculations with and without nuclear heat sources have been entered in Table 1 (Cases 4 and 5). The comparison with Cases 1 and 2 shows an increase of the maximum temperature. The temperature distribution, however, is not affected significantly.

Although electrical heating of the threaded ends of the specimens is technically almost impossible, such a concept was investigated as Case 6. The heated section is depicted in the bottom part of Fig. 8. The electrical power density was increased to 170 W/cm^3 in order to achieve a significant reduction of the temperature difference in the specimens. The calculated temperature distribution is shown in Fig. 9. The maximum and minimum temperature reach now values of 585 °C and 543 °C, respectively. $L_{5\%}$ amounts to 0.83, i.e. the constancy of the temperature distribution is significantly improved (s. Table 1, Case 6). However, the temperature in the region of the specimen support has increased, too: The temperatures of the screw cap and the adapter are now at about the same level as the specimen itself.

Finally, a design variant was investigated with modified cooling conditions in the region of the specimen support. A small guide tube is attached to the helium supply tube in such a way that a gap with stagnant helium is generated reducing the cooling in this region (see bottom of Fig. 8). The analytical results for this design variant - with and without nuclear power - have been included in Table 1 (Cases 7 and 8). The temperature distribution for Case 7 is shown in Fig. 10. The comparison with Cases 1 and 2 shows a reduction of the maximum temperature and simultaneously an improvement of the temperature constancy. E.g. the constancy criterion $L_{5\%}$ in Case 7 amounts to 52 % compared to 46 % for the reference design (Case 1).

5. Conclusions

The most important conclusions drawn from the investigations described above can be summarized as follows:

1. The proposed heating and cooling concept allows the adjustment and control of the envisaged irradiation temperatures of the specimens without major problems.
2. However, significant temperature differences will occur along the axis of the specimens. E.g. in the case of the reference design, the fraction of the specimen length with a temperature variation of less than 5 % (referred to the coolant inlet temperature) amounts to only 46 % (with nuclear power) and 38 % (without nuclear power), respectively.
3. The reduction of the local heat transfer by inserting a guide tube in the area of the specimen support increases in the case with nuclear power the length fraction with almost constant temperature from 46 to 52 %.
4. A further significant improvement of the temperature distribution could be reached by an additional electrical heating of the threaded ends of the specimens. However, such a concept is technically hardly feasible.
5. The other design variants investigated were found to be less suitable.
6. Whether the temperature differences occurring in the specimens can be tolerated must be clarified by the material specialists with regard of the objectives of the tests.
7. The direct electrical heating to establish and control the specimen temperature requires high electrical currents. The space needed for cables and power connections may be significant and must be determined in the further design work.

6. References

[1] M. Martone (Ed.): IFMIF International Fusion Materials Irradiation Facility. Conceptual Design Activity, Final Report, IFMIF CDA Team, ENEA Frascati, Report ENEA-RT/ERG/FUS/96-11, Dec. 1996.

[2] IFMIF International Team: IFMIF-KEP – International Fusion Materials Irradiation Facility, Key Element Technology Phase Report. Japan Atomic Energy Research Institute, JAERI-Tech 2003-005, March 2003.

[3] A. Möslang: Personal communication.

[4] S. P. Simakov: Personal communication.

[5] P. Vladimirov: Personal communication.

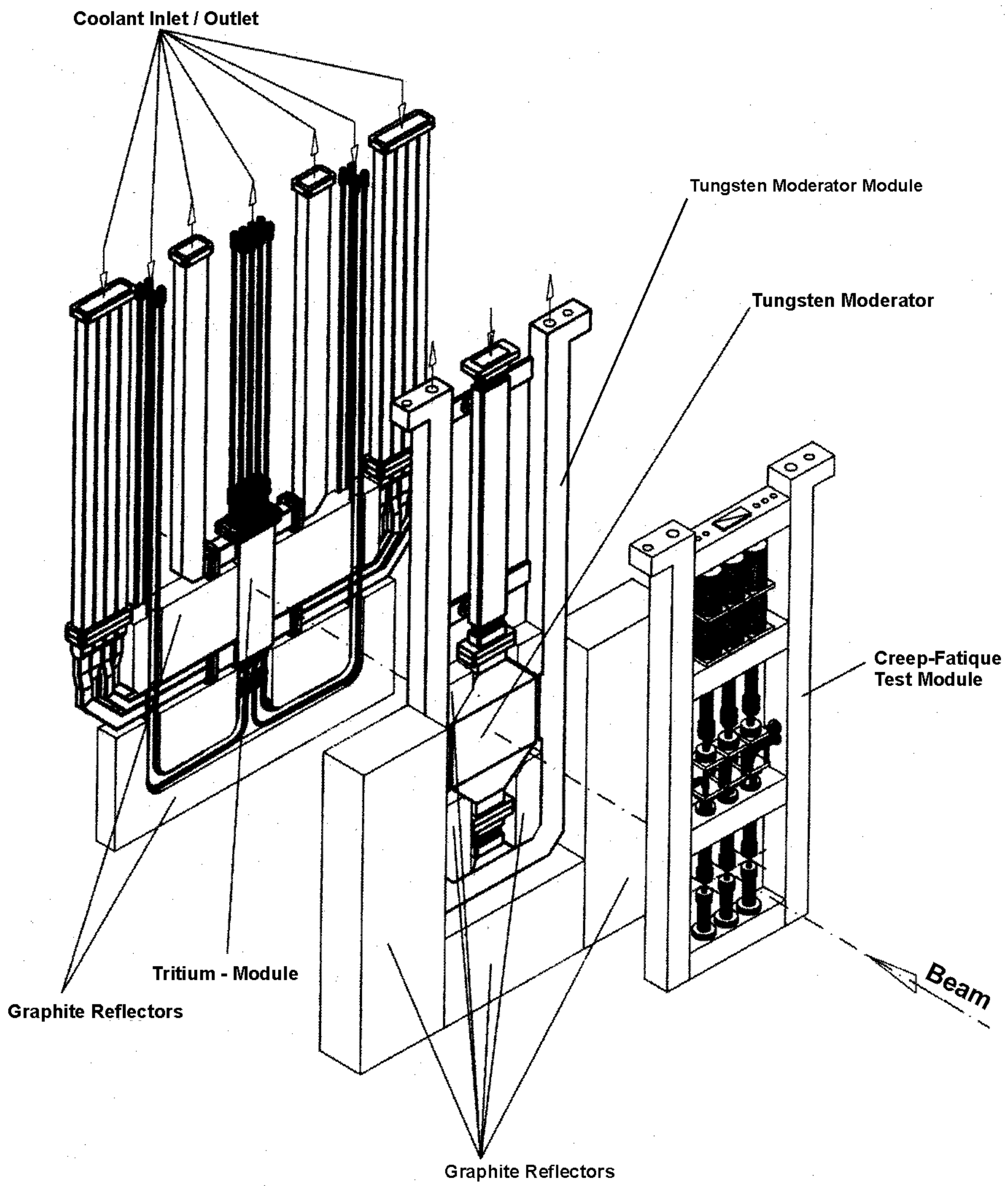


Fig. 1: Exploded view of the submodules of the Medium Flux Test Module

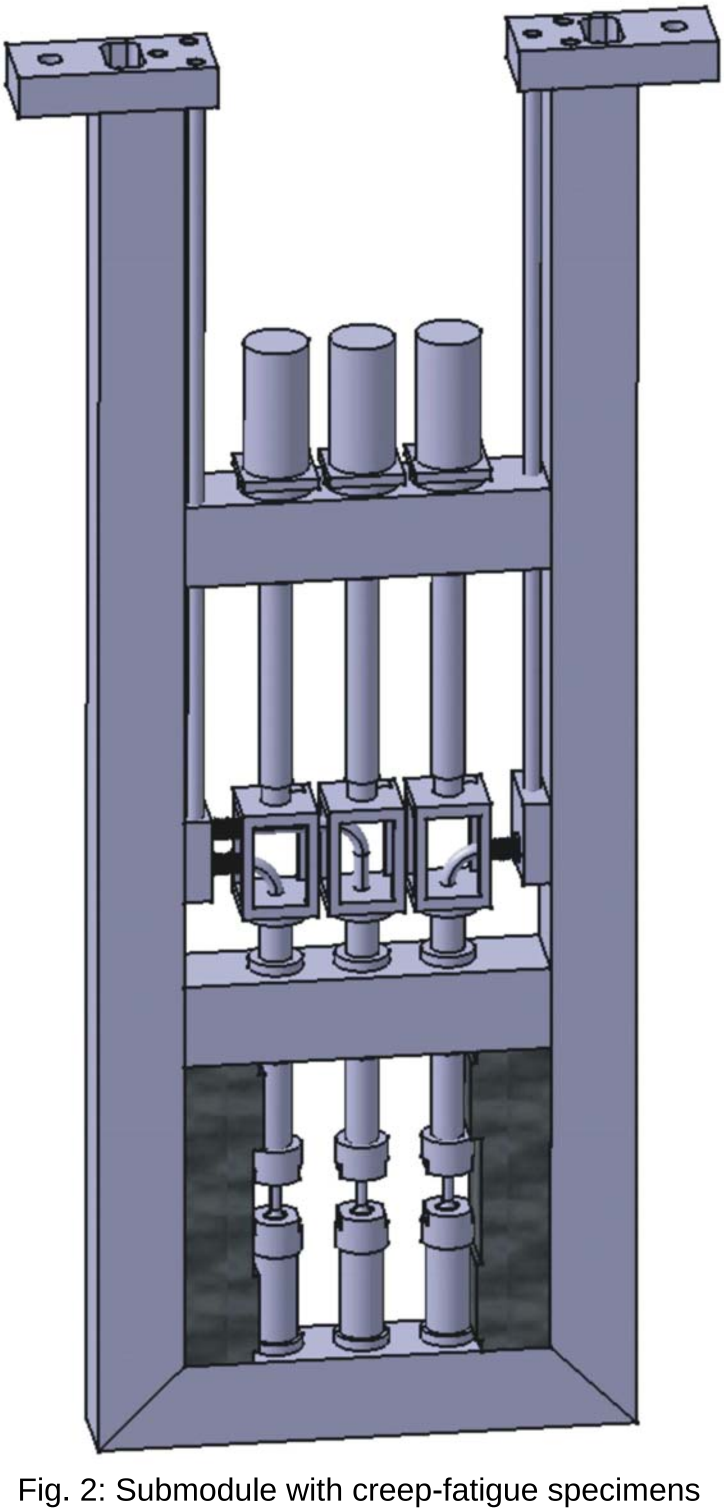


Fig. 2: Submodule with creep-fatigue specimens

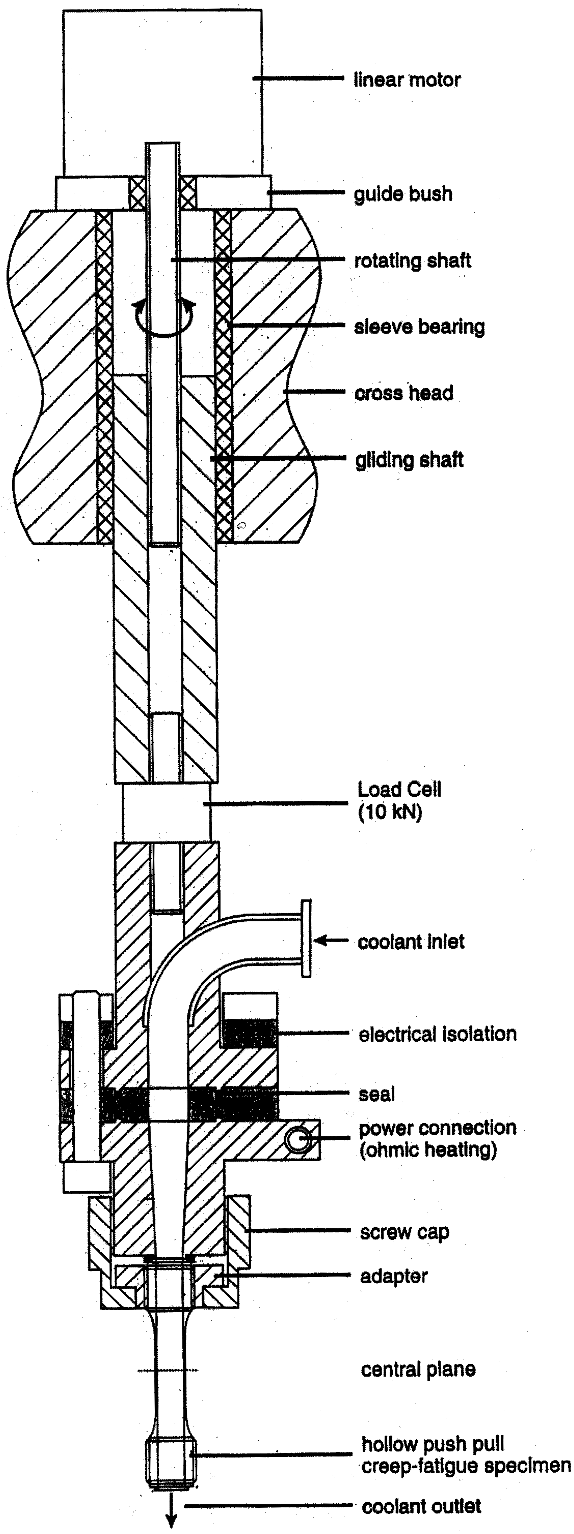


Fig. 3: IFMIF In-situ creep-fatigue experiments - Preliminary design of rod drive

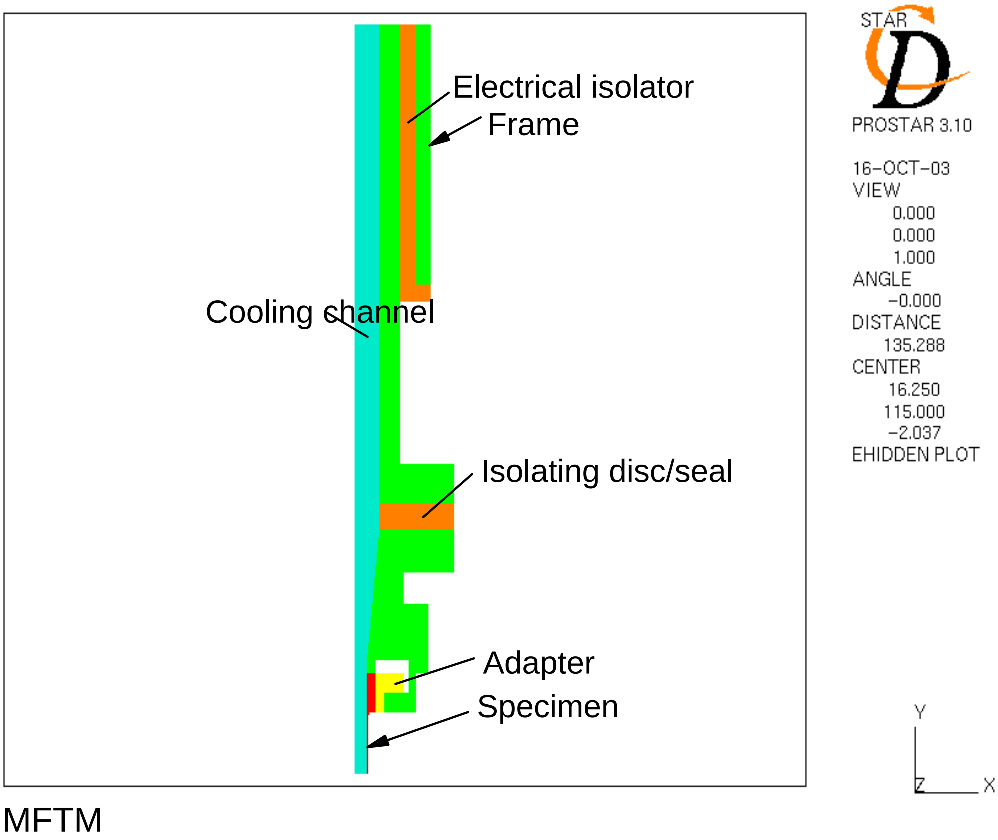


Fig. 4: Model of the thermal-hydraulic simulations using the CFD-Code STAR-CD

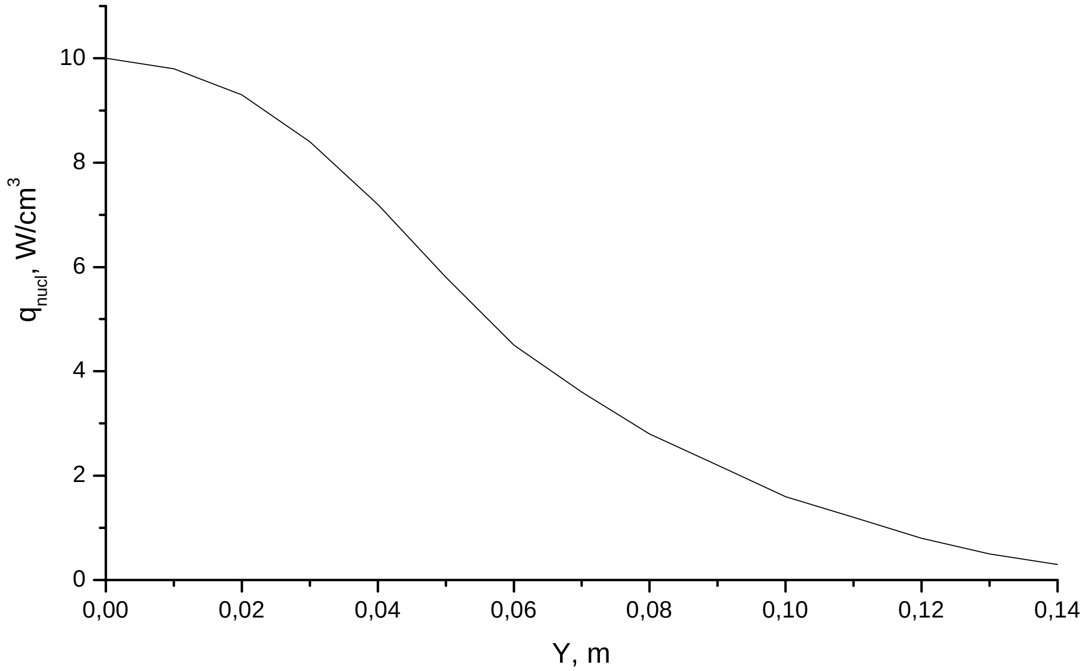
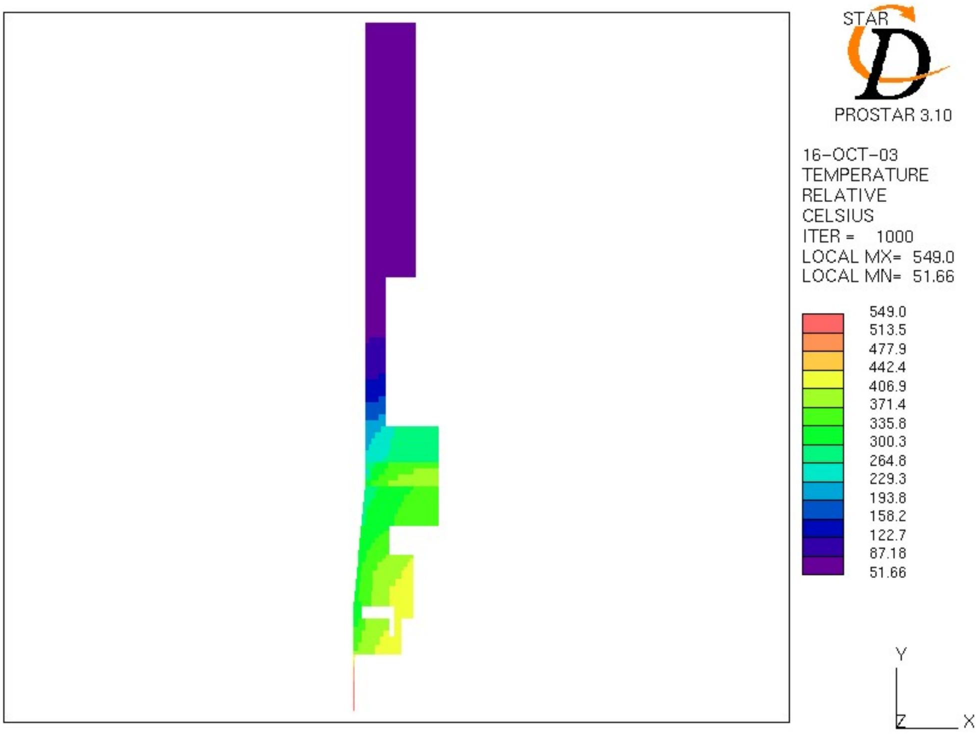


Fig. 5: Nuclear power density in steel along the axis of the central creep-fatigue specimen (extrapolated from data of the HFTM)



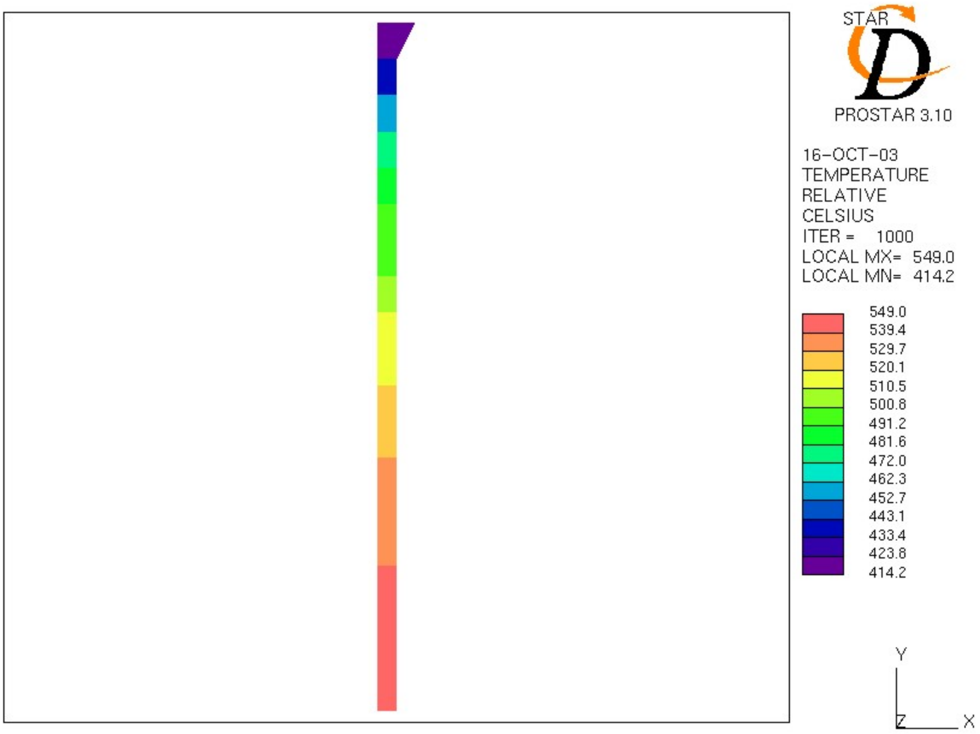
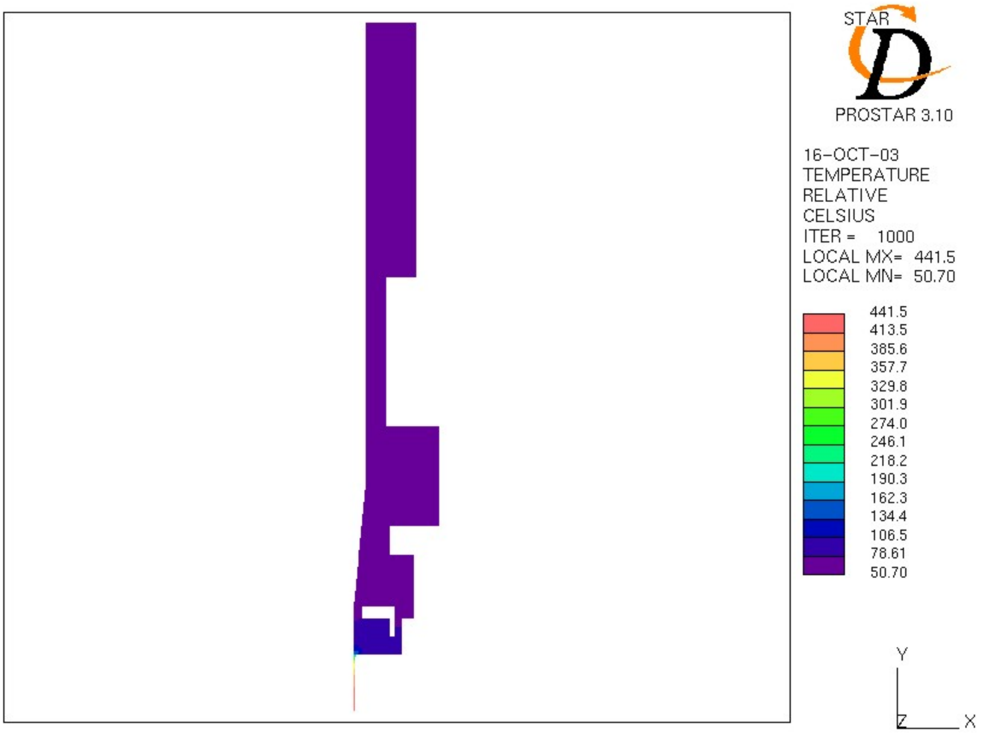


Fig. 6: Temperature distribution in the creep-fatigue test assembly calculated with STAR-CD, Case 1 (reference concept, with nuclear power)
Top: entire model; bottom: specimen only.



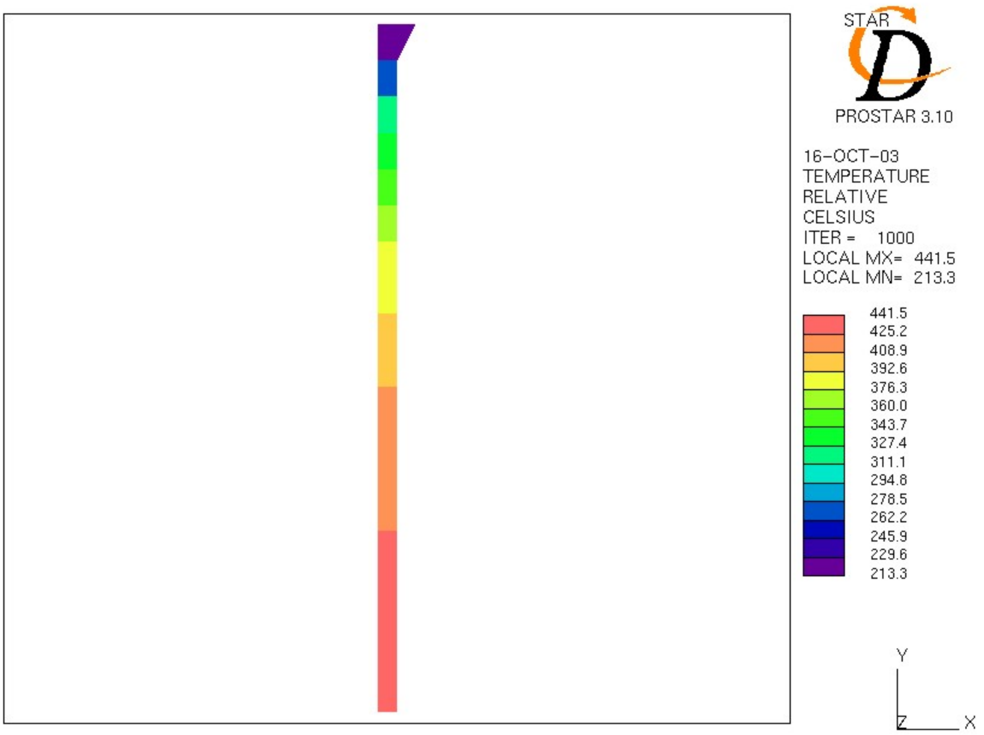
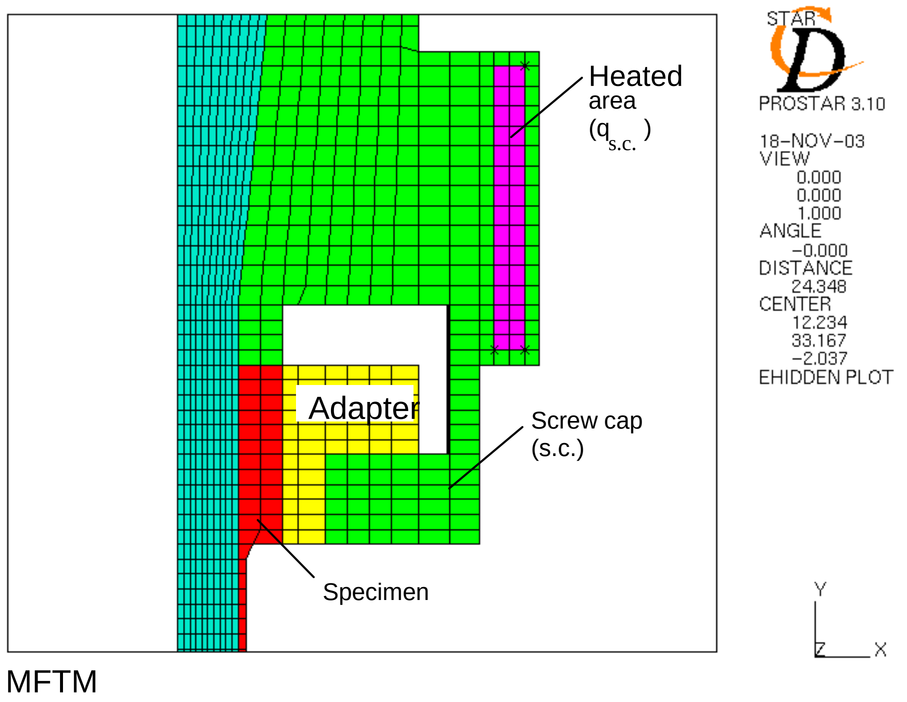


Fig. 7: Temperature distribution in the creep-fatigue test assembly calculated with STAR-CD, Case 2 (reference concept without nuclear power)
Top: entire model; bottom: specimen only.



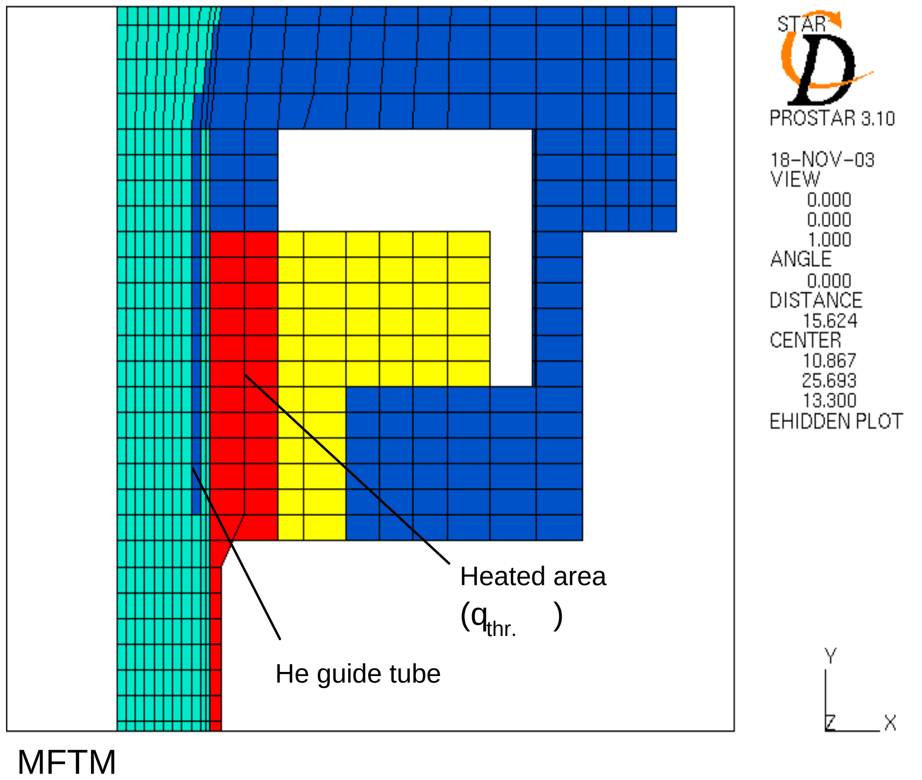


Fig. 8: Design variants with additional electrical heating in the screw cap (top) and in the specimen thread (bottom), and with helium guide tube (bottom)

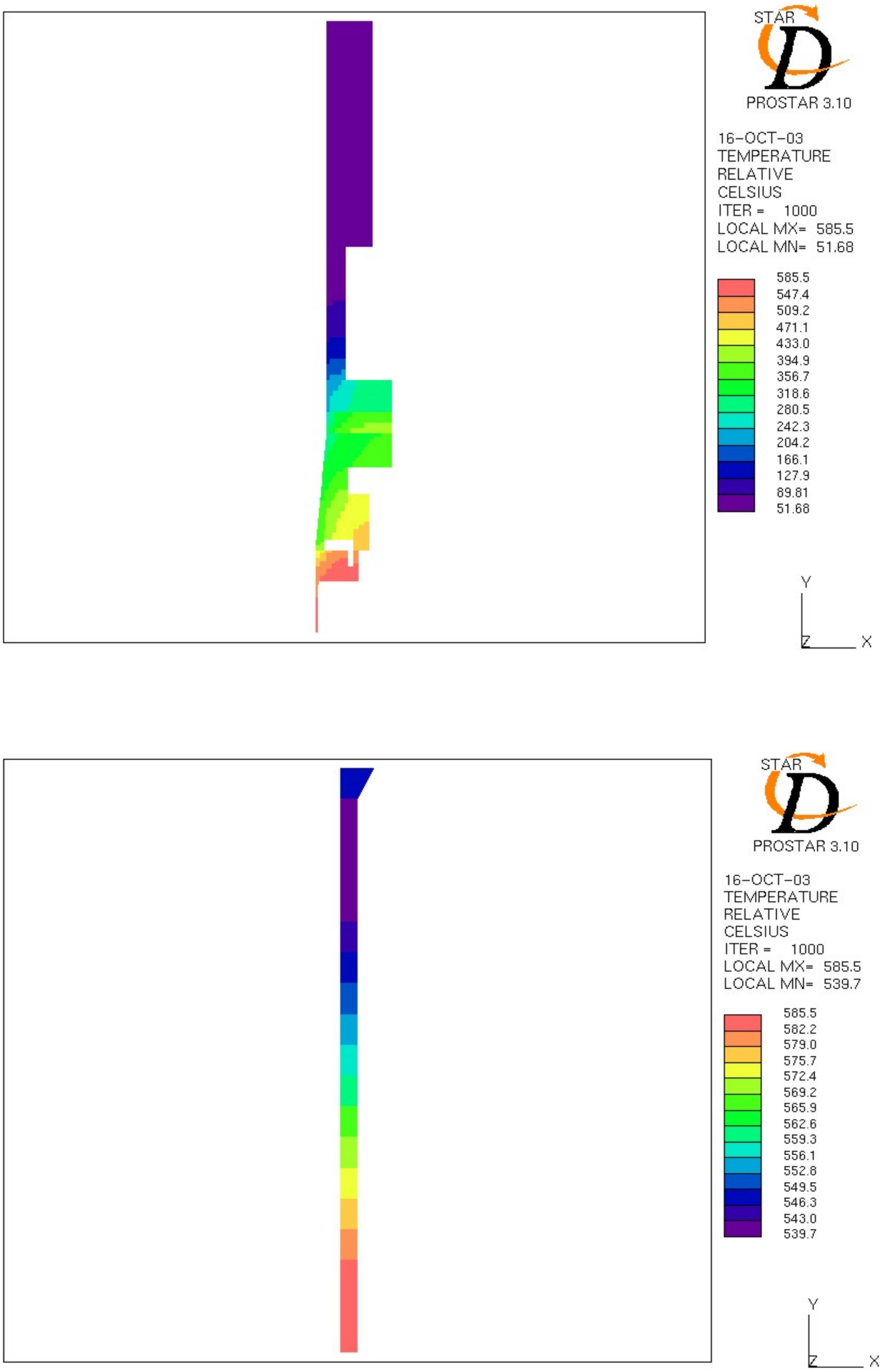
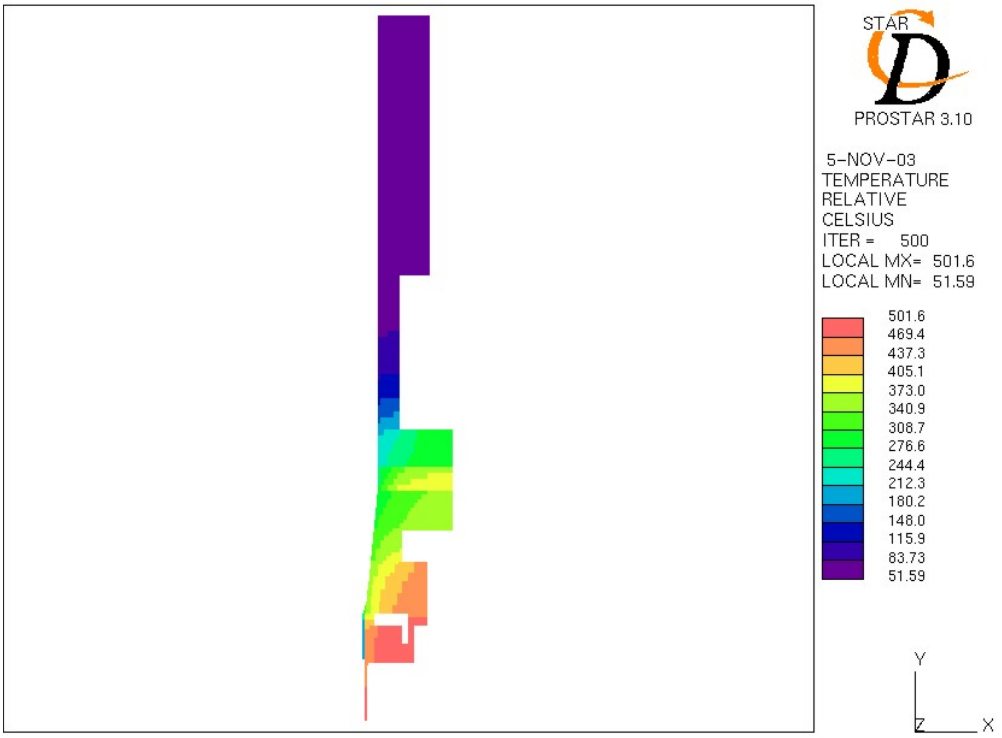


Fig. 9: Temperature distribution in the creep-fatigue test assembly calculated with STAR-CD, Case 6 (design variant with ceramic adapter and electrical power generation in the specimen thread, with nuclear heating)
Top: entire model; bottom: specimen only.



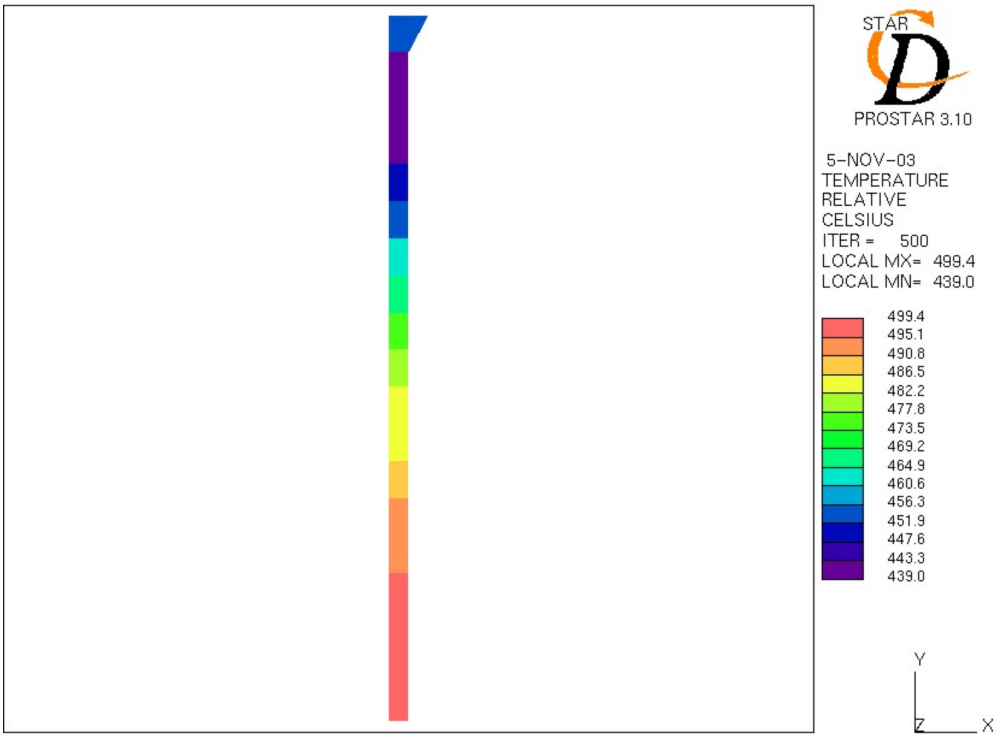
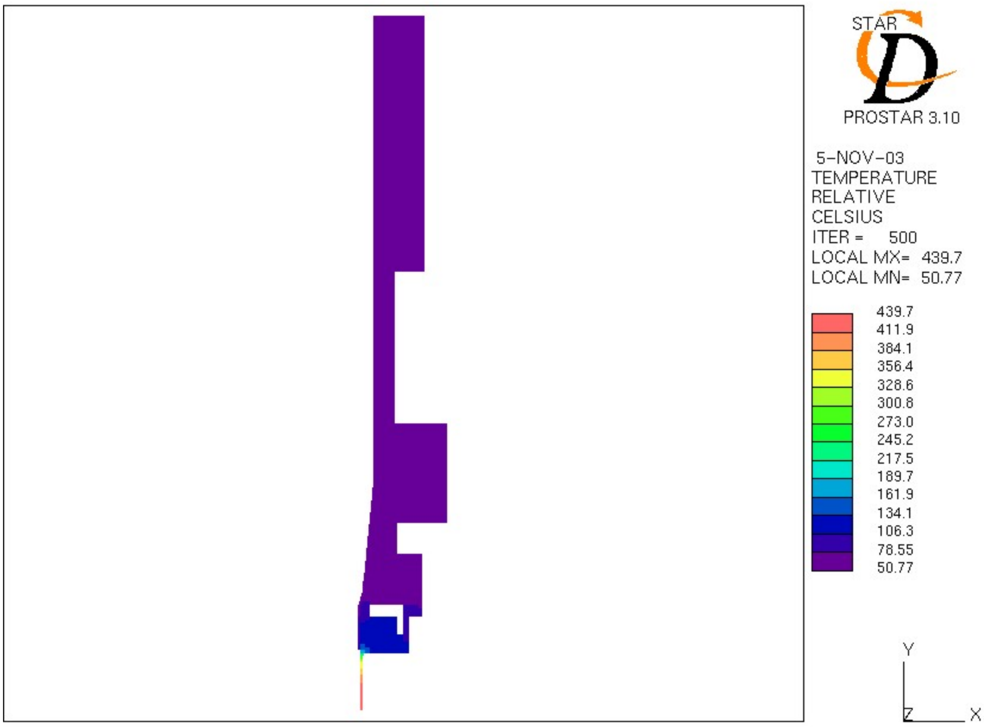


Fig. 10: Temperature distribution in the creep-fatigue test assembly calculated with STAR-CD, Case 7 (design variant with helium guide tube, with nuclear power)
Top: entire model; bottom: specimen only.



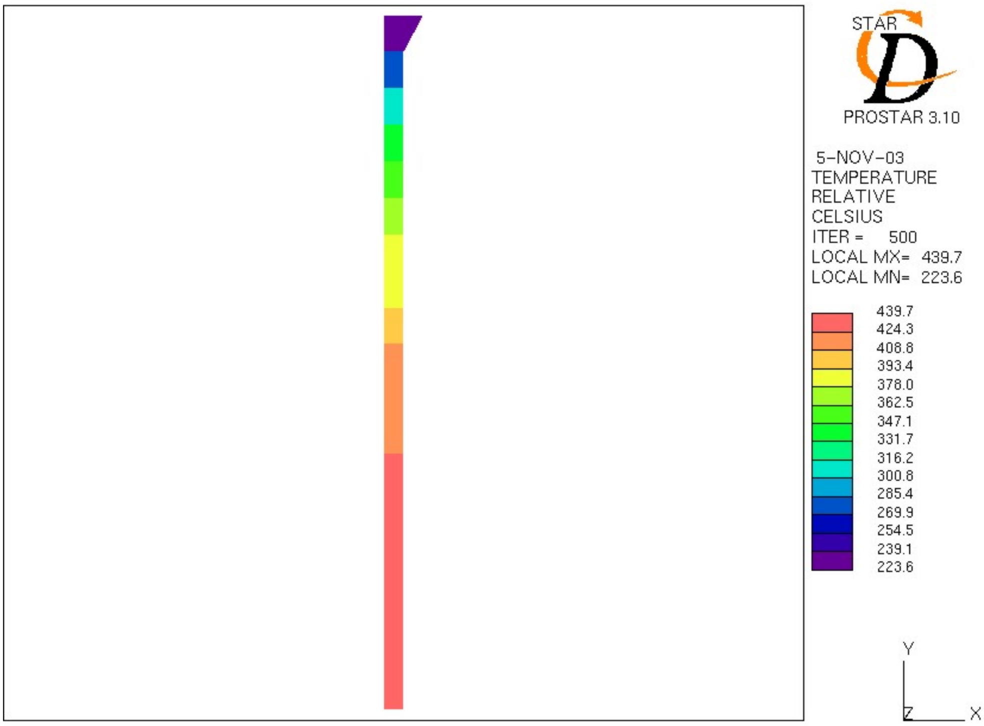


Fig. 11: Temperature distribution in the creep-fatigue test assembly calculated with STAR-CD, Case 8 (design variant with helium guide tube, without nuclear power) Top: entire model; bottom: specimen only.