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HTR-N

HTR-N & N1
High-Temperature Reactor Physics and Fuel Cycle Studies
(EC-funded Projects: FIKI-CT-2000-00020 & FIKI-CT-2001-00169)

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Document Title

Definition of common parameters and reference HTR designs for HTR-N[1]

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2	31 08 2004	Comments from partners (see minutes of HTR-N Mid-Term Review Meeting) incorporated in final issue. Title has been changed.

HTR-N

Definition of common parameters and reference HTR designs for HTR-N[1]

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Petten, 31. August 2004

20570/04.61610/C

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CONTENTS

1 INTRODUCTION

Work Package 3 of the **HTR-N** contract [1] is concerned with the assessment of the performance of the fuel types (in different reactor systems) to be investigated with respect to Pu-incineration capabilities, economics and safety, with emphasis on Pu-incineration. Initially, the emphasis in the HTR-N project was on the incineration of *1st generation* (civil) plutonium. Due to reductions in the **HTR-N1** contract [2] with respect to the original proposal [3], the work program in HTR-N Work Package 3 has been redefined [4] to include also *2nd generation* plutonium from recycled LWR MOX fuel.
This document is an extended version of the document originally intended as **Deliverable 3.1.1** of the HTR-N contract. In this document the basic parameters of the reference pebble bed as well as block type HTRs will be presented, as well as the reference coated particle definitions (*1st generation* and *2nd generation* civil) plutonium composition and the required output parameters, to be calculated for intercomparison of the different concepts and cases under study. Additionally, also the definition is included of a "Plutonium cell burnup benchmark" (for *1st* and *2nd generation* civil plutonium), as agreed in Work Package 3 (Task 3.1) of the HTR-N1 contract.
This document includes the complete information from the following *supporting documents* as respective Appendices:

A) Definition of **reference coated particles** and **plutonium compositions (1st and 2nd generation Pu)** [5]. This part of the document is also intended as the **Deliverable 3.2.1** of the **HTR-N1** contract [2] as it also contains reference data on *2nd generation* plutonium. The original document also contains as Appendices the Minutes of the HTR-N WP3 meetings of 24 April 2002 and 28 May 2004, and a note by B. Bonin and D. Greneche concerning the isotopic composition of plutonium from UOX and MOX fuels in LWRs. These have been included as well.
B) Specification of HTR-MEDUL core for different fuel cycles [6]. This is the definition of the **reference continuous reload pebble-bed HTR**. The dimensions of the fuel kernel and the coating layers of the coated particles are specified in Appendix A.
C) Fuel element physical parameters for Pu fuel cycles in a prismatic block type core [7]. This is the definition of the **reference hexagonal block type HTR**.
D) Definition of **common output parameters** [8]. This is the definition of the common set of safety-, (Pu-) transmutation performance- and economics related parameters to be calculated for each of the fuel types/HTR combinations under study by different partners, in order to facilitate the assessment and intercomparison.
E) **Sample output format** for common output parameters [9].
F) **Plutonium (1st and 2nd generation) cell burnup benchmark** [10]. Although this is activity of part of the HTR-N1 contract, it was considered appropriate to include it in this document as well, so that this document contains all basic/reference information for the HTR reactor physics and fuel cycle analyses within both HTR-N and HTR-N1.

The supporting documents mentioned above have all been included into SINTER as well. However, the corresponding Appendices in this report may contain **additional and/or improved** data.

2 REFERENCES

[1] European Fifth Framework Program Contract no. FIKI-CT-2000-00020 “HTR-N”, signed 4. September 2000.
[2] European Fifth Framework Program Contract no. FIKI-CT-2001-00169 “HTR-N1”, signed 20. September 2001.
[3] European Fifth Framework Program Proposal no. 2000-014 “HTR-N1”, January 2001.
[4] J.C. Kuijper & W. von Lensa, “Revised work program for WP3: Physics Analysis of Different Fuel Cycles”, Document HTR-N-01/6-D-3.0.1 in SINTER, 20. June 2002.
[5] J.C. Kuijper, H.J. Ruetten & B. Bonin, “Definition of reference coated particles and plutonium compositions (1st and 2nd generation Pu)”, Document HTR-N-02/06-D-3.1.4 in SINTER, 25. June 2002.
[6] H.J. Ruetten, “Specification of HTR-MEDUL Core for different fuel cycles”, Document HTR-N-00/10-D-3.1.2 in SINTER, 17. October 2000.
[7] X. Raepsaet, “Fuel element physical parameters for Pu fuel cycles in a prismatic block type core”, Document HTR-N-00/12-D-3.1.3 in SINTER, 26. April 2002.
[8] J.C. Kuijper & J.B.M. de Haas, “Definition of common output parameters”, Document HTR-N-01/02-D-3.1.5 in SINTER, 20. June 2002.
[9] Sample output file “SAMPLE_FORMAT.20020620.txt”, Document HTR-N-02/06-S-3.1.1 in SINTER, June 2002.
[10] H.J. Ruetten & J.C. Kuijper, “Plutonium (1st and 2nd generation) cell burnup benchmark specification”, Document HTR-N1-02/06-S-3.1.1 in SINTER, 11. March 2003.

A REFERENCE COATED PARTICLES AND PU COMPOSITIONS

Original documents

(Sections A.1 - A.3) J.C. Kuijper, H.J. Ruetten & B. Bonin, "Definition of reference coated particles and plutonium compositions (1st and 2nd generation Pu)", Document HTR-N-02/06-D-3.1.4 in SINTER, 25. June 2002 [5].
(Section A.4) Minutes of HTR-N WP3 meetings of 24 April 2002 and 28 May 2002 [A3].
(Section A.5) B. Bonin and D. Greneche, "Isotopic composition of the plutonium coming from UOX and MOX fuel burning in light water reactors" [A4].

Additional remarks

This Appendix is also intended as **Deliverable 3.2.1** of the **HTR-N1** contract [2], as it also contains reference data on *2nd generation* plutonium.

The composition of *first generation* plutonium, as proposed by Rütten, FZJ [A1] (composition "A", "*1st generation (original)*"), is a working assumption, based on experience of the FZJ laboratory.

A.1 REFERENCE COATED PARTICLE DEFINITIONS

The properties of the coated particles to be used in the analyses of HTR-N/N1 Work Package 3 have been defined in [A1], while additional information on the fuel density and the coating layer dimensions has been obtained later on [A2].

Reference fuel kernels

Fuel	Density [g cm^{-3}]	Diameter [mm]	Max. allowed burnup [MWd/kg]
UO_2	10.4	0.50	800
PuO_2	10.4	0.24	800
ThO_2	10.4	0.50	120
$(U\text{-}Th)O_2$	10.4	0.50	120
$(Pu\text{-}Th)O_2$	10.4	0.50	120

Coating material and dimensions

Coating layer material	Density [g cm^{-3}]	Thickness [mm]
C	1.05	0.095
C	1.90	0.040
SiC	3.18	0.035
C	1.90	0.040

The packing fraction in the compact/pebble should be derived from the desired fuel content per compact/pebble.
It should be noted that no impurities are assumed in the coated particles.

A.2 REFERENCE PLUTONIUM COMPOSITIONS

In the course of the HTR-N/N1 project a number of plutonium compositions have been defined, which are to be used in the envisaged analyses. These compositions are given below, together with 2 real (experimental) Pu compositions used in two Petten HFR irradiation experiments, viz. “THORIUM” [A5] and “OTTO” [A6].

Isotope	***1st generation* (original) (A)**	***1st generation* (alternative) (B)**	***2nd generation* (C)**	**“THORIUM”**	**“OTTO”**
Unit	**weight %**	**weight %**	**weight %**	**atom %**	**weight %**
^{238}Pu	1	2.59	4.9	1.74	0.60
^{239}Pu	62	53.85	26.9	59.49	68.18
^{240}Pu	24	23.66	34.3	24.92	21.54
^{241}Pu	8	13.13	15.3	7.43	7.01
^{242}Pu	5	6.78	18.6	5.74	2.67
^{241}Am	-	-	-	0.68	-

The *1st generation* (original) (A) Pu composition is the one originally proposed by Rütten in [A1] and agreed upon by the WP3 partners in [A3]. The *1st generation* (alternative) (B) and *2nd generation* (C) Pu compositions were proposed by Bonin and Greneche in [A4], and also agreed upon in [A3]. It should be noted that the Pu composition of (C) is consistent with that of (B). The “THORIUM” and “OTTO” compositions have been listed as examples of real (experimental) Pu compositions, which can be used as variations on the base cases (to be analysed by interested WP3 partners).

As was confirmed in [A3], the *1st generation* (original) Pu composition (A) will be the reference composition used in **HTR-N** Task 3.2a (“Fuel cycles with continuous reload – *1st generation* Pu”) and Task 3.3a (“Fuel cycles with batch-wise reload – *1st generation* Pu”) [A7]. The alternative *1st generation* Pu (B) can be regarded as one of the variations on the base case (to be analysed by one partner).

The *2nd generation* (C) Pu composition will be the reference composition for based calculations in **HTR-N** Task 3.2b (“Fuel cycles with continuous reload - *2nd generation* Pu”) and Task 3.3b (“Fuel cycles with batch-wise reload - *2nd generation* Pu”).

The *1st generation* (alternative) (B) and *2nd generation* (C) Pu compositions (both!) will be the reference compositions for the “Pu cell burnup benchmark” of **HTR-N1** Task 3.1 [A8]. However, the original *1st generation* reference composition can again be regarded as a variation on the base case (to be analysed by one partner).

A.3 REFERENCES

[A1] H.J. Rütten, “Specification of HTR-MEDUL core for different fuel cycles”, Document HTR-N-00/10-D-3.1.2 in SINTER, 17. October 2000.

[A2] H.J. Rütten, private E-mail communication, 31. January 2001.

[A3] J.C. Kuijper, Minutes of WP3 meeting d.d. 28. May 2002, NRG note NRG/FAI/jkuijper/20206131, 14. June 2002, Attachment 12 to HTR-N/N1 5th Project Management Meeting information in SINTER; see Section A.4.

[A4] B. Bonin & D. Greneche, “Isotopic composition of the plutonium coming from UOX and MOX fuel burning in light water reactors”, Note attached to E-mail d.d. 12. December 2001 from B. Bonin (COGEMA) to W. von Lensa (FZJ) and J.C. Kuijper (NRG); see Section A.5.

[A5] R. Conrad, K. Bakker, R. Schram & C.M. Sciolla, “THORIUM CYCLE – Irradiation Experiment on Thorium Based Fuel Targets in a SHIFT Sample Holder at the HFR Petten”, TECHNICAL MEMORANDUM HFR/01/4661, EC/JRC Petten, 21. August 2001 (*confidential*).

[A6] K. Bakker, R. Conrad, C.M. Sciolla & R.P.C. Schram, “OTTO – Design & Safety Report”, NRG Report 20003/00.35216/C, 5. September 2000 (*confidential*).

[A7] J.C. Kuijper & W. von Lensa, “Revised work program for WP3: Physics Analysis of Different Fuel Cycles”, Document HTR-N-01/6-D-3.0.1 in SINTER, 20. June 2002.

[A8] H.J. Rütten & J.C. Kuijper, “Plutonium cell burnup benchmark (first and second generation Pu)”, Document HTR-N1-02/06-S-3.1.1 in SINTER; see Appendix F.

A.4 MINUTES OF HTR-N WP3 MEETINGS [A3]

```
                  NOTE NRG/FAI/jkuijper/20206131
Author        :       Kuijper J.C. (NRG Petten)
To            :   HTR-N/N1 WP3 partners

Copy to       :   -

Date          :   14-Jun-2002

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Project       :       HTR-N and HTR-N1

Subject       :   Minutes WP3 meetings d.d. 24 April 2002 and 28 May 2002
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== WP1/2/3 meeting Petten d.d. 24 April 2002 ==
* Agenda

1. Opening/agenda
2. Minutes of WP3 meeting on 20. November 2001 (Juelich)
3. Arrangements for forthcoming PMM in Pisa (27/28 May 2002)
4. Present status of activities/contributions to management report
   a. WP1
   b. WP2
   c. WP3
5. Status of pending actions/update of action list(s)/actions to be
   completed before PMM in Pisa
6. Final version of revised WP3 work program
7. Common parameters (common output; Pu-vectors)
8. Pu cell burnup benchmark
9. Any other business
10. Closing

* Announcements/Discussion

The mid-term review will be at the end of 2002. A special area in
SINTER is reserved for illustrations (to be used in the mid-term
report). All partners should provide illustrations.
The mid-term report will also be sent to external reviewers.  Making a good impression is important
as it coincides with the call for proposals for the 6th FP.
All contributions to WP3 should use the new format cover page as designed by Ansaldo.
The expected completion dates in the “Revised work program for WP3” (SINTER document HTR-N-01/6-D-
3.0.1) should be adapted to the actual situation in order to avoid late deliveries. Mr. Kuijper will
take care of this.
Sylvie Casalta (ex-JRC Petten) is the new administrative officer in Brussels for the HTR-N and HTR-
N1 projects.

== WP3 meeting Pisa d.d. 28 May 2002 ==
* Agenda

1. Work program (revision)
2. Common (output) parameters
3. Reference Pu vector(s) and coated particle dimensions
4. Pu cell burnup benchmark
5. Action list

* Announcements/Discussion

The WP3 partners agree to the latest revised edition of the
“Revised work program for WP3” (SINTER document HTR-N-01/6-D-3.0.1).
Some final adjustments to the expected completion dates were made.
Mr. Kuijper will put these adjustements into the final version
of the document.
The definition of common output parameters for intercomparison is being discussed (SINTER document
HTR-N-01/2-D-3.1.5). It is agreed upon that the main emphasis is on the data items concerned with
mass balances and fuel/waste composition. It is agreed that a list of specific nuclides is added for
which mass balances etc. have to be calculated. The WP3 partners also agree on the proposed format.
Mr. Kuijper will include these extensions in the final version of the document. It is the
responsability of the partners to supply data for intercomparison to the Work Package Manager in the
correct form.
The WP3 partners agree on the proposed 1st and 2nd generation Pu vectors, as summarised in  the E-
mail of Mr. Kuijper of 21.  December 2001. The relevant part of the text of that E-mail is given
below:
QUOTE>>
...
* The origin of the Pu-I composition as proposed by Mr. Bonin (viz. 2.59/53.85/23.66/13/13/6.78
weight%) is clear, which is an advantage compared to the reference Pu-I composition agreed upon in
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the “common parameters” (viz. 1/62/24/8/5 weight%). The proposed Pu-II composition is consistent with the newly proposed Pu-I composition.
* However, the 1/62/24/8/5 reference Pu-I composition has already been used in a large part of the analysis work (mainly by FZJ and IRI).

So I propose the following:
* The original 1/62/24/8/5 Pu-I composition remains the reference Pu-I composition for the “Pu-I” based calculations in HTR-N Task 3.2a (“Fuel cycles with continuous reload - 1st generation Pu”) and Task 3.3a (“Fuel cycles with batch-wise reload - 1st generation Pu”). However, the newly proposed Pu-I composition can be regarded as one of the variations on the base case (to be analysed by one partner).
* The proposed Pu-II composition (4.9/26.9/34.3/15.3/18.6 weight%) will be the reference composition for “Pu-II” based calculations in HTR-N Task 3.2b (“Fuel cycles with continuous reload - 2nd generation Pu”) and Task 3.3b (“Fuel cycles with batch-wise reload - 2nd generation Pu”).
* The newly proposed Pu-I and Pu-II compostions (both!) will be the reference compositions for the “Pu cell burnup benchmark” of HTR-N1 Task 3.1. However, the original reference Pu-I compostion can again be regarded as a variation on the base Pu-I case (to be analysed by one partner).
...
<<UNQUOTE
The WP3 partners also agree on the proposed coated particle dimensions (as stated in SINTER document HTR-N-00/10-D-3.1.2).
The HTR-N1 WP3 “Pu cell burnup benchmark” was discussed. This benchmark has been defined by Mr. Ruetten (FZJ). It is agreed that the calculations will be performed for both 1st and 2nd generation Pu (see above). Mr. Kuijper will add a list of nuclides and a required data format to the benchmark specification and transform it into the new document format. The WP3 partners also agree that the proposed Pu cell burnup benchmark will also be used for the sensitivity studies in the framework of HTR-N WP2. This has to be confirmed by the HTR-N WP2 Work Package Manager.
Mr. Kuijper will check and update the WP3 action list and subsequently send it to the WP3 partners for review.

A.5 NOTE BY B. BONIN AND D. GRENECHE [A4]

Isotopic composition of the plutonium coming from UOX and MOX fuel burning in light water reactors

Bernard Bonin and Dominique Grenèche, COGEMA, Direction de la Recherche et du Développement

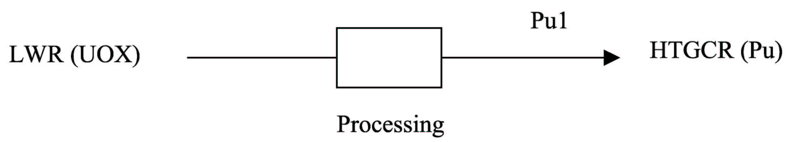
High Temperature, Gas-Cooled Reactors (HTGCR) have long been recognized as promising plutonium burners. In order to assess this potentiality, the HTR-Collaboration intends to revisit core physics and fuel cycle scenarios for plutonium-burning HTGCRs, with modern methods and in the light of the most recent data.

These studies require an important input, *i.e* the isotopic composition of the plutonium fuel to be burnt in the HTGCR.

In the present note, we propose a set of isotopic vectors for this Pu fuel, assuming a realistic origin for the plutonium.

In fact, two realistic sources of plutonium can be envisaged :

I. "Plutonium1", coming from the processing of the UOx fuel spent in present light Water Reactors (LWRs).



For calculating the "Pu1" isotopic composition, we assume the following characteristics for its origin :

Use of a PWR reactor (REP900-type), burning UOx fuel with an enrichment of 3.7%, with a cycle length of 274 full power equivalent days, and a staying time of 4 cycles for each fuel element. This corresponds to a burnup of 41.2 GWd/t, representative of the current day practice.

The isotopic composition of the Pu1 has been calculated with the code CESAR (ref. 1).

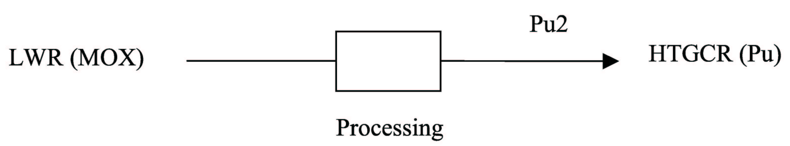
After a cooling time of 3 years following the end of the irradiation, the calculated composition is as follows (last column of Table 1):

Pu1	% (weight) (HTR-N Benchmark)	% (weight) (CESAR)
238	1	2.59
239	62	53.85
240	24	23.66
241	8	13.13
242	5	6.78

Table 1. The isotopic composition of first generation Plutonium. The middle column is the Pu1 composition assumed so far by the HTR benchmark; The right column is the Pu1 composition as calculated by the code CESAR with the hypotheses described in the text.

The isotopic composition of Pu1 has been agreed upon in the frame of the "Pu benchmark" of HTR-N (ref. 2). As can be seen from Table 1 (middle column), this plutonium is very rich in fissile isotopes. The hypotheses underlying its composition are not clear, and cannot be found in ref. 2. Extrapolation of the CESAR calculations enables to trace back the origin of this isotopic vector : the corresponding plutonium could come from irradiation of UOx fuel at a low burnup, of the order of 25 GWd/t. Unless a very "rich" Pu vector is found desirable for the benchmark, we recommend to restart the exercise with a more realistic isotopic composition, like the one calculated by CESAR, given in Table 1, with the hypotheses described above.

II. "Plutonium2" coming from the processing of 1-loop MOX fuel spent in LWRs.



For calculating the "Pu2" isotopic composition, we assume the following characteristics for its origin :

-Use of PWR reactors (EPR-type) burning 100% MOX fuel, with an initial composition consistent with the Pu1 given in Table 1, taking into account 2 additional years delay for MOX fuel fabrication.

-Uranium support for this MOX fuel was assumed to be depleted U (0.25%), and the Pu concentration in the mixture was assumed to be 7.49%.

-The residence time of a fuel element was assumed to be 5 cycles, with a cycle length of 254 full power equivalent days. This corresponds to a burnup of 56 GWd/t, hopefully representative of the future state-of-the art (we do not forget that HTR will not be introduced immediately in reactor fleets, and we therefore allow for technical progress in MOX burnup).

-The isotopic composition of the Pu2 was calculated using the code KAFKA (réf. 1), for a fuel cooling time of 3 years.

Pu2	% (weight)
238	4.9
239	26.9
240	34.3
241	15.3
242	18.6

Table 2. Isotopic composition of second-generation plutonium.

With Pu1 and Pu2, we have two extreme plutonium isotopic compositions. It can be seen that this Pu2 is severely degraded as compared to Pu1, and has significantly less fissile isotopes. Subsequent core studies should tell us under which conditions HTGCRs can burn this second-generation plutonium. After this preliminary step, fuel cycle studies will then proceed on a sound basis and with verified hypotheses.

Ref. 1 : "Données de Base Réacteurs pour les Etudes de Prospaective", J. Guyot et al. CEA Tech. Note SIS/SPRC 95-1007 (Nov. 1995)

Ref. 2 : HTR-N Annual Report 2001

B REFERENCE CONTINUOUS RELOAD PEBBLE-BED HTR

Original document

(**Section B.1**) H.J. Rütten, “Specification of HTR-MEDUL core for different fuel cycles”, Document HTR-N-00/10-D-3.1.2 in SINTER, 17. October 2000 [6]

Additional remarks

The dimensions of the fuel kernel and the coatings in the coated particles are as specified in Appendix A “Reference coated particles and Pu compositions”.

B.1 REFERENCE DATA OF SIMPLIFIED HTR-MODUL

The reference continuous reload pebble bed reactor is a simplified HTR-MODUL [B1] operating in continuous reload mode ("MEDUL - German: "MEhrfach DurchLauf" - multi-pass). The following tables contain a description of this system. The main approximation is the use of a "flat bottom" instead of a conically shaped defuelling chute. Consequently a uniform vertical flow velocity distribution of the pebbles over the entire radius of the core is assumed. So in the pebble re-circulation model the fuel pebbles leave the reactor core "through" the flat bottom. Geometry and material zones are shown in **Fig. B.1**.

Table I: Main Data of the MEDUL-HTR for Pu-burning

Core height	9.43 m
Core diameter	3.0 m
Nominal power	200 MWth
Power density in the core	3.0 MW/m^3
Thermal efficiency	40 % (assumed in calculations)
Number of fuel elements/ m^3	5394
Helium temperature	
Core inlet	250 °C
Core outlet	700 °C
Helium pressure, core inlet	60 bar
Helium mass flow rate	85.55 kg/s
Basic density of graphite in reflectors	1.80 g/cm^3

Table II: Nuclide Densities in reactor zones

(see Fig. C.1; boron is added to graphite in order to simulate impurities;)

Zone Nr.		Densitiy [**cm** $^{-1}$ **barn** $^{-1}$]	
1	Reflector	N_C = 7.72 E-02	N_B = 1.31 E-08
2	Void		
3	Void + graphite	N_C = 2.00 E-03	N_B = 3.40 E-10
4	Reflector	N_C = 9.03 E-02	N_B = 1.54 E-08
5	Carbon	N_C = 8.53 E-02	N_B = 4.98 E-03
6	Reflector + coolant channels	N_C = 7.02 E-02	N_B = 1.19 E-08
7	Reflector + control rods	N_C = 3.51 E-02	N_B = 7.27 E-06
8	Reflector	N_C = 3.51 E-02	N_B = 5.96 E-09

Table III: Fuel Element Specifications

Diameter of pebbles	6 cm
Diameter of fuel zone	5 cm
Density of graphite	1.75 g/cm^3

Possible variants of the coated particles: (also see Appendix A):

Coating layers	C / C / SiC /C
Density	1.05 /1.90 /3.18 /1.90 g cm^{-3}

Fuel	**Diameter of kernel**	**Maximum burnup allowed**
UO_2	0.50 mm	800 MWd/kg
PuO_2	0.24 mm	800 MWd/kg
ThO_2	0.50 mm	120 MWd/kg
$(U\text{-}Th)O_2$	0.50 mm	120 MWD/kg
$(Pu\text{-}Th)O_2$	0.50 mm	120 MWD/kg

Isotopic composition of typical "1. Generation"- LWR-Pu:

Pu-38	/Pu-39	/Pu-40	/Pu-41	/Pu-42 =
1	/62	/24	/8	/5 weight %

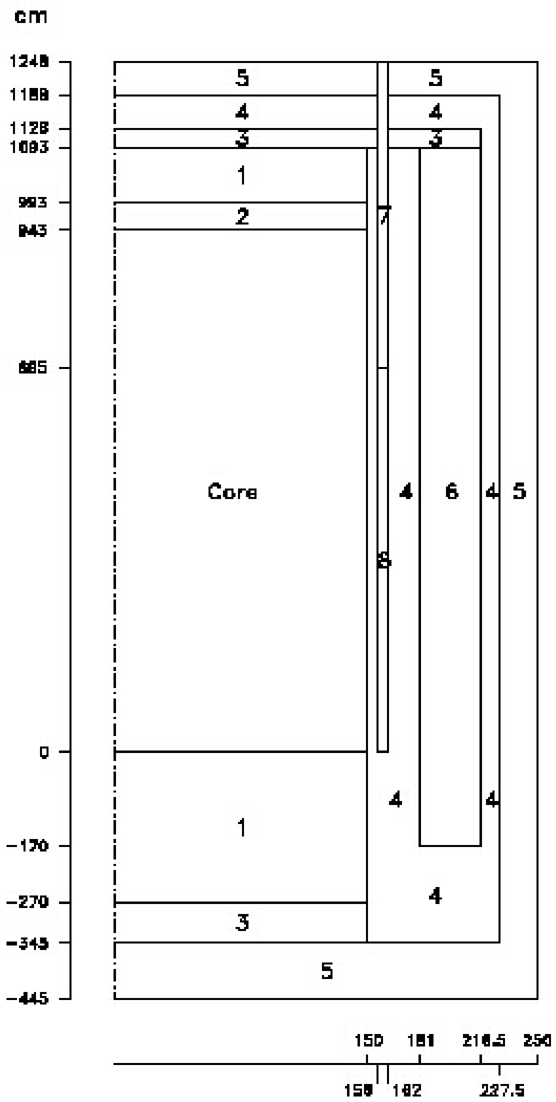


Fig. B.1 Main dimensions and material regions of the calculational model of the HTR-MODUL. Dimensions are in cm. The core is a random stacking of the well-known 6 cm fuel balls (‘pebbles’). The conical defuelling chute below the core is not modelled. Other (more or less homogenised) material regions in the model are: (1) reflector (graphite), (2) void (so He gas), (3) homogenised void and graphite, (4) reflector (graphite), (5) carbon bricks, (6) reflector with coolant channels, (7) reflector with control rod channels, (8) reflector (graphite).

B.2 REFERENCES

[B1] Reutler and G.H. Lohnert, “The Modular High-Temperature Reactor”, *Nuclear Technology*, **62**, 22–30, 1983.

C REFERENCE HEXAGONAL BLOCK TYPE HTR

Original document

(**Section C.1**) X. Raepsaet, "Fuel element physical parameters for Pu fuel cycles in a prismatic block type core", Document HTR-N-00/12-D-3.1.3 in SINTER, 26. April 2002 [7]

Additional remarks

The PuO_2 density specified (viz. 10.0 g/cm^3), the PuO_2 kernel diameter, and some thicknesses of the particle coatings are different from the ones specified in Appendix A "Reference coated particles and Pu compositions".

C.1 REFERENCE DATA OF GT-MHR

The reference hexagonal block type HTR is based upon the GT-MHR [C1]. The core of the GT-MHR consists of 102 columns of fuel comprising 72 standard element columns and 30 control element columns. The reflector and fuel columns consist of stacks of prismatic blocks with a height of 80 cm and 36.0 cm across opposite sides. The core of the GT-MHR also includes a reflector at the top and the bottom with a height of 130 cm. Details are shown in Figs. C.1 to C.3. Main parameters are listed below.

Core power	600	MWth
Core power density	6.6	MW/m^3
Thermal efficiency	48	% (assumed in analyses)
Loading factor	0.85	(assumed in analyses)
Core inlet outlet He temperatures	491/850	Celsius
Helium pressure	7	MPa
(Average core temperatures for fuel/graphite	*800/750*	*Celsius)*
Core columns	102	
Number of fuel elements	1020	(10/column)
Standard	720	(10/column)
Control	300	(10/column)
Active core height	800	cm
Equivalent diameter of active core zone	296 / 484	cm
height of axial reflectors	130	cm
Hexagonal fuel dimensions		
Flat to flat	36	cm
Height	80	cm
Central fuel handling hole		
Diameter	40	mm
Height	380	mm
Control rod hole diameter	130	mm
Fuel compact diameter	12.45	mm
Fuel compact length	49.3	mm
Compacts in fuel hole	15	
Coolant hole diameter		
Small	12.70	mm
Large	15.88	mm
Holes available for fuel and poison	216/174	*standard/control element*
Number of coolant holes		
Small	6/5	*standard/control element*
Large	102/84	*standard/control element*

Example of poison particle (natural boron)

B_4C kernel (diameter)	200	µm
Buffer coating (thickness)	18	µm
Pyrocarbon coating (thickness)	23	µm

Fuel particles

see HTR-N-00/10-D-3.1.2 (or Appendix A)

fuel kernel (diameter)	200	µm
coatings C/C/SiC/C (thickness)	100/35/35/40	µm

Plutonium isotopic composition

see HTR-N-00/10-D-3.1.2 (or Appendix A)

PuO_2 density	10.0	g/cm^3
Graphite density	1.74	g/cm^3

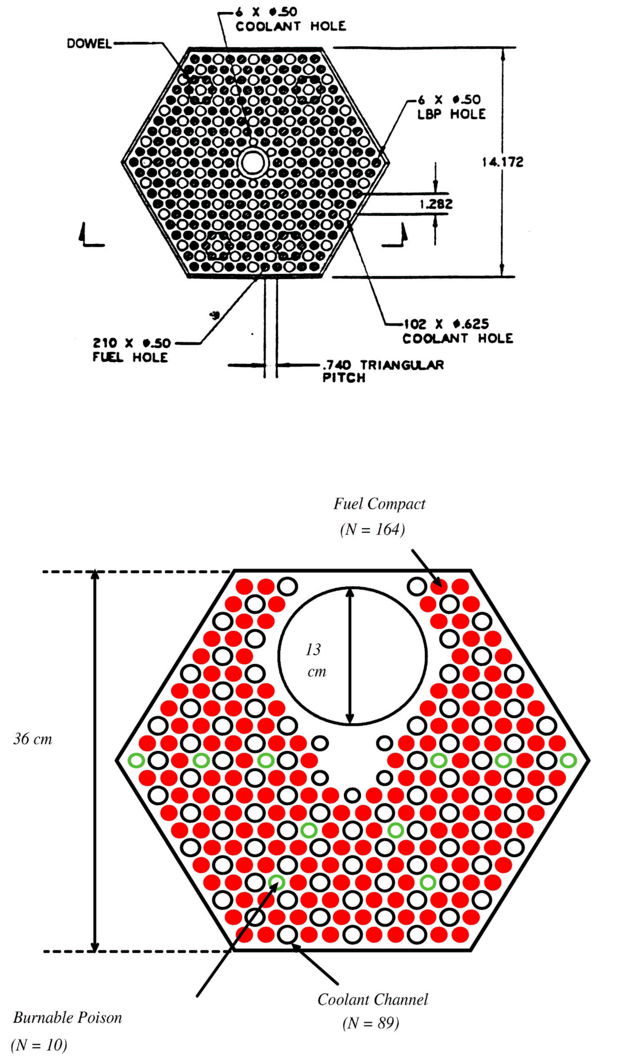


Fig. C.1 Standard (upper) and control (lower) fuel blocks (top view) of the GT-MHR**.**

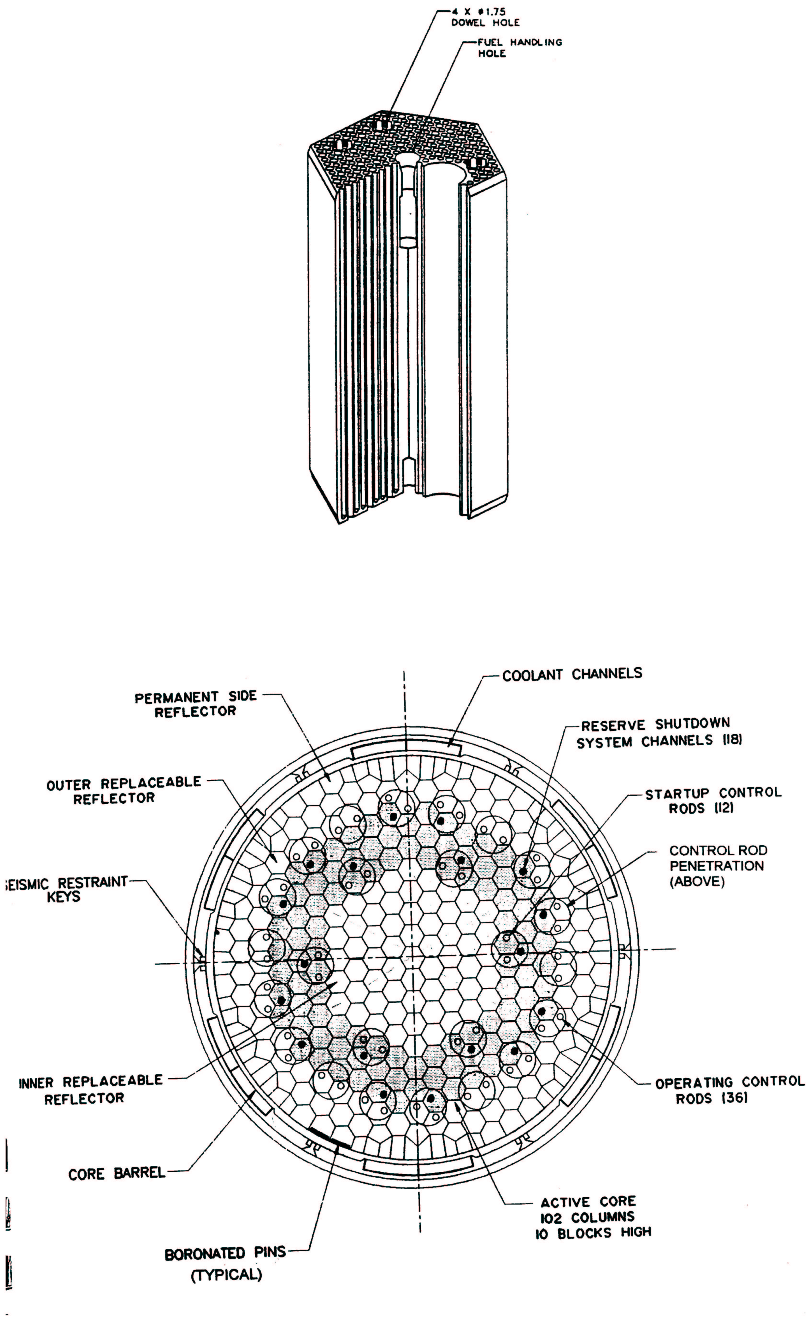


Fig. C.2 GT-MHR fuel block (upper) and core layout (lower).

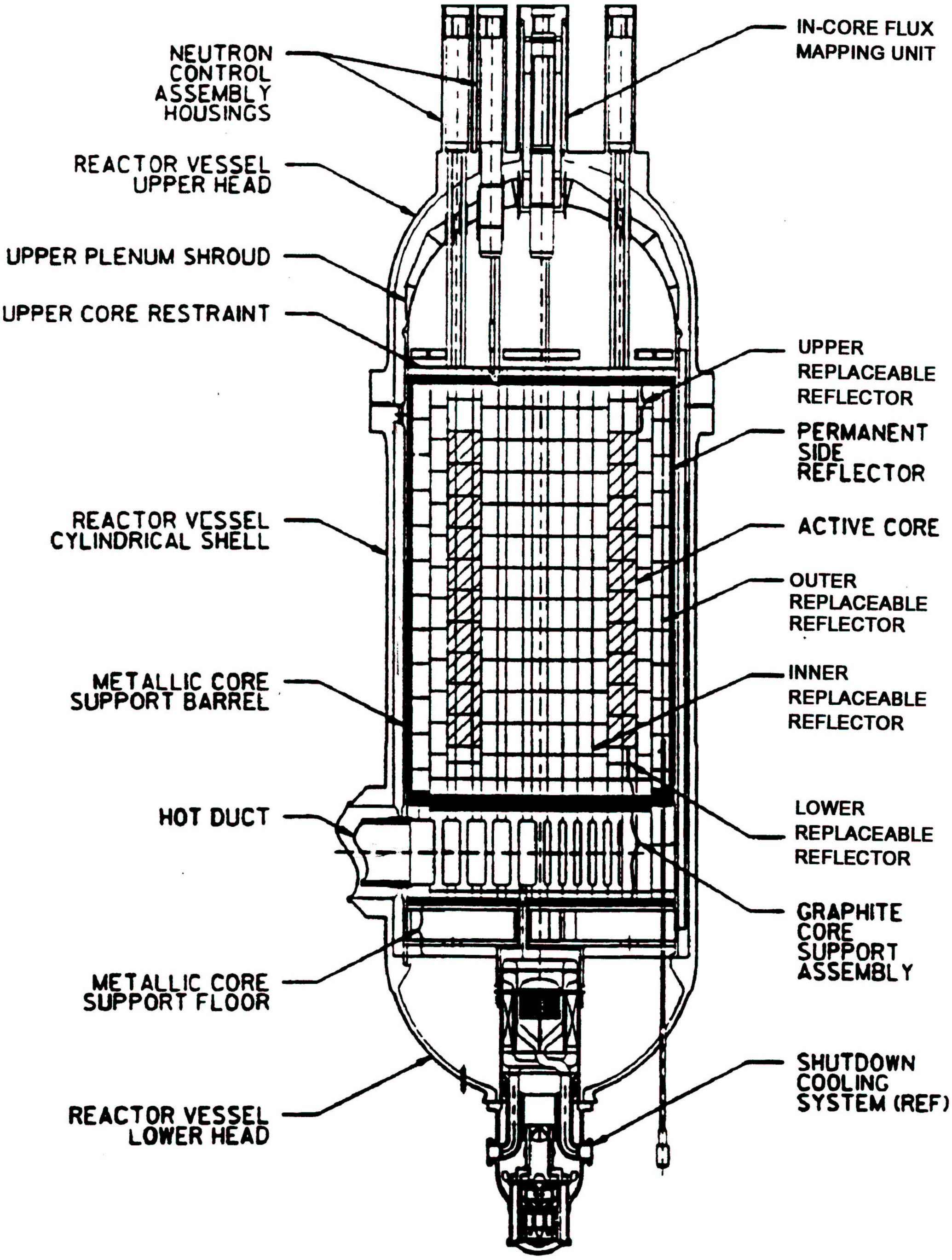


Fig. C.3 600 MWth GT-MHR reactor vessel internals.

C.2 REFERENCES

[C1] General Atomics, “Gas Turbine Modular Helium Reactor conceptual design report”, July 1996.

D COMMON OUTPUT PARAMETERS

Original document

(**Sections D.1 - D.5**) J.C. Kuijper & J.B.M. de Haas, “Definition of common output parameters”, Document HTR-N-01/02-D-3.1.5 in SINTER, 20. June 2002 [8].

Additional remarks

A listing of the sample output file “SAMPLE_FORMAT.20020620.txt” [10] has also been included in this document. See Appendix E.

D.1 INTRODUCTION

Work Package 3 of the HTR-N project is concerned with the performance of the fuel types (in different HTR systems) to be investigated with respect to Pu-incineration capabilities, economics and safety. In order to be able to intercompare the results for different fuels in different reactor systems, obtained by different partners, a common set of economics and safety related output parameters is presented here, which are to be calculated for the fuel type/reactor system combinations under investigation. The parameters can be calculated on coated particle-, compact-/pebble-, block- and reactor level, depending on the fraction of the entire system taken into account in the calculation. For a real intercomparison a full 3-D calculation on the entire reactor level is desirable. However, calculations on a fraction of the reactor system (coated particle, compact/pebble, block) may also yield useful information, e.g. on the influence of burnable poison on certain parameters. The parameter set listed below is intended as code-independent, data library-independent and system-independent as possible. However, some parameters may seem -and actually are- redundant or superfluous for the specific system (part) under consideration, while it may not always be possible to calculate all requested parameters for the specific system (part) under consideration with the available code system and/or nuclear data libraries. Also parameters have been included which are not directly economics and safety related, but which are intended to support interpretation of calculation results.

D.2 REQUESTED PARAMETERS FOR INTERCOMPARISON

In the following it is assumed that the reactor system is at 100% of its nominal thermal power for a fraction of its operating cycle length, equal to the capacity factor. For a system with continuous reload, like the HTR-MODUL pebble-bed reactor, the operating cycle length is -somewhat arbitrarily- defined as 1 year = 365 days. For other systems, the operating cycle length is defined as the number of days between successive starts of operating cycles (so operation time + reload stop). The Beginning of Life ("BOL") is the point in time of the start of the operating cycle (reactor at nominal thermal power), the End of Life ("EOL") is the end of the full power operation time (beginning of possible reload stop). The Mid of Life ("MOL") is the point in time exactly between BOL and EOL. For a continuous reload system (in the equilibrium state) the values of parameters at BOL, MOL and EOL will be identical. The following information/parameters should be supplied/calculated.

It should be noted that the parameter sets considered the most important for the assessment and intercomparison of transmutation capabilities and safety are 2, 3, 4, 7 and 8.

0. Case identification and description.
    - 0.1. Origin
    - 0.2. Organisation
    - 0.3. Case number
    - 0.4. Date
    - 0.5. Applied code system
    - 0.6. References

1. General fuel/reactor/system specifications. This section is intended as a complete description of the fuel, the reactor (system) and the applied fuel loading and discharge scheme.
    - 1.1. System (part) under consideration (reactor, supercell, etc.)
    - 1.2. Main system dimensions
    - 1.3. Coated particle dimensions (kernel and coatings) (per coated particle type)
    - 1.4. Initial coated particle composition per nuclide per material zone (units: $(\text{barn cm})^{-1}$) (per coated particle type; including impurities)
    - 1.5. Compact/pebble dimensions
    - 1.6. Compact/pebble composition per nuclide (outside coated particles; including impurities) (units: $(\text{barn cm})^{-1}$)
    - 1.7. Block composition per nuclide (outside coated particles; including impurities) (units: $(\text{barn cm})^{-1}$)
    - 1.8. Number of coated particles per pebble compact (of each coated particle type)
    - 1.9. Operating cycle length (units: full power days)
    - 1.10. Reload stop duration (units: days) (may be 0 in case of continuous reload, in which case EOL coincides with the end of the operating cycle)
    - 1.11. Nominal reactor power (units: MW)
    - 1.12. Capacity factor (units: -)
    - 1.13. Number of fuel batches (batch wise reload only) (units: -)
    - 1.14. Nominal coolant inlet temperature (units: K)
    - 1.15. Nominal coolant inlet pressure (units: Pa)
    - 1.16. Nominal coolant outlet temperature at nominal (Hot Full Power, HFP) conditions (units: K)
    - 1.17. Nominal coolant outlet pressure at nominal (Hot Full Power, HFP) conditions (units: Pa)
    - 1.18. Nominal coolant mass flow (unit: kg/s)
    - 1.19. Description of fuel cycle strategy and other relevant information on the specific case.

2. Rating and power density
    - 2.1. Power produced per coated particle (per coated particle type) (units: W):
        - 2.1.1. Maximum value occurring anywhere in the core at any time during the operating cycle
        - 2.1.2. Maximum value anywhere in the core as function of time over the operating cycle

- 2.2. Power produced per compact/pebble (units: W)
  - 2.2.1. Maximum value occurring anywhere in the core at any time during the operating cycle
  - 2.2.2. Maximum value anywhere in the core as function of time over the operating cycle
- 2.3. Power produced per unit heavy metal mass (units: W/kg)
  - 2.3.1. Maximum value occurring anywhere in the core at any time during the operating cycle
  - 2.3.2. Maximum value anywhere in the core as function of time over the operating cycle
- 2.4. Power density in the core (units: W/m^3)
  - 2.4.1. Maximum value occurring anywhere in the core at any time during the operating cycle
  - 2.4.2. Maximum value anywhere in the core as function of time over the operating cycle

3. Core inventory
   - 3.1. Amount of each of the heavy metal isotopes present in the core (units: kg)
     - 3.1.1. At BOL
     - 3.1.2. At MOL
     - 3.1.3. At EOL
   - 3.2. Fissile Pu fraction, i.e. amount of (^{239}Pu and ^{241}Pu) divided by the total amount of Pu (units: -) (this can be derived from 3.1)
     - 3.2.1. At BOL
     - 3.2.2. At MOL
     - 3.2.3. At EOL

4. Fuel (actinide) consumption, actinide and fission product production and discharge burnup at nominal conditions. A list of nuclides under consideration is presented in section 4.
   - 4.1. Amount and composition of fresh fuel loaded into the system for one operating cycle (per heavy metal nuclide) divided by the operating cycle length (units: kg/year)
   - 4.2. Amount and composition of fuel discharged from (and not reloaded into) the system for one operating cycle (per heavy metal and fission product nuclide) divided by the operating cycle length (units: kg/year)
   - 4.3. Balance of heavy metal and fission products, i.e. the difference between corresponding items 4.1 and 4.2, divided by nominal thermal power times capacity factor (units: kg/MWd)
   - 4.4. Attained discharge burnup of the fuel (units: MWd/kg)
     - 4.4.1. Minimum value
     - 4.4.2. Average value
     - 4.4.3. Maximum value

5. Reaction rates at nominal conditions
   - 5.1. Neutron induced fission rate per heavy metal nuclide in the entire system (units: s^{-1})
     - 5.1.1. At BOL
     - 5.1.2. At MOL
     - 5.1.3. At EOL
   - 5.2. Neutron absorption rate for all (heavy metal, fission product and possibly burnable poison) nuclides present in the kernels of all coated particles (units: s^{-1}) (per nuclide)
     - 5.2.1. At BOL
     - 5.2.2. At MOL
     - 5.2.3. At EOL
   - 5.3. Neutron absorption rate in all other material in the core cavity (units: s^{-1}) (per nuclide, including burnable poison if present)
     - 5.3.1. At BOL
     - 5.3.2. At MOL
     - 5.3.3. At EOL
   - 5.4. Net neutron leakage rate from the core cavity (units: s^{-1})
     - 5.4.1. At BOL
     - 5.4.2. At MOL
     - 5.4.3. At EOL

6. Fast and thermal neutron flux (fluence rate) and fluence measures at nominal conditions
   6.1. Thermal flux below 1.86 eV (units: $m^{-2}s^{-1}$). The items listed below should be calculated at BOL, MOL and EOL.
      6.1.1. Average value in the core
      6.1.2. Peak value in the core
      6.1.3. Average value in the reflector
      6.1.4. Peak value in the reflector
      6.1.5. Axial distribution of the thermal flux along the centre axis
      6.1.6. Radial distribution of the thermal flux at half core height
   6.2. $^{59}Co(n,\gamma)$ reaction rate of a 10^{-10} $(barn\ cm)^{-1}$ trace of ^{59}Co in all materials in the core and reflector. This is a measure of the thermal flux below ~1 eV, which is independent of the energy group structure employed in the calculations. The items listed below should be calculated at BOL, MOL and EOL.
      6.2.1. Total reaction rate in the core (units: s^{-1})
      6.2.2. Total reaction rate in the reflector (units: s^{-1})
      6.2.3. Peak value of the reaction rate density in the core (units: $s^{-1}m^{-3}$)
      6.2.4. Peak value of the reaction rate density in the reflector (units: $s^{-1}m^{-3}$)
      6.2.5. Axial distribution of the reaction rate density along the centre axis (units: $s^{-1}m^{-3}$)
      6.2.6. Radial distribution of the reaction rate density at half core height (units: $s^{-1}m^{-3}$)
   6.3. Fast flux (fluence rate) above 0.1 MeV (units: $m^{-2}s^{-1}$). The items listed below should be calculated at BOL, MOL and EOL.
      6.3.1. Average value in the core
      6.3.2. Peak value in the core
      6.3.3. Average value in the reflector
      6.3.4. Peak value in the reflector
      6.3.5. Axial distribution of the fast flux along the centre axis
      6.3.6. Radial distribution of the fast flux at half core height
   6.4. $^{58}Ni(n,p)$ reaction rate of a 10^{-10} $(barn\ cm)^{-1}$ trace of ^{58}Ni in all materials in the core and reflector. This is a measure of the fast flux above ~2 MeV, which is independent of the energy group structure employed in the calculations. The items listed below should be calculated at BOL, MOL and EOL.
      6.4.1. Total reaction rate in the core (units: s^{-1})
      6.4.2. Total reaction rate in the reflector (units: s^{-1})
      6.4.3. Peak value of the reaction rate density in the core (units: $s^{-1}m^{-3}$)
      6.4.4. Peak value of the reaction rate density in the reflector (units: $s^{-1}m^{-3}$)
      6.4.5. Axial distribution of the reaction rate density along the centre axis (units: $s^{-1}m^{-3}$)
      6.4.6. Radial distribution of the reaction rate density at half core height (units: $s^{-1}m^{-3}$)
   6.5. Fast fluence above 0.1 MeV of discharged fuel (kernel, coatings, matrix) (units: m^{-2})
      6.5.1. Minimum value
      6.5.2. Average value
      6.5.3. Maximum value

7. Temperatures at nominal conditions
   7.1. Coated particle temperature (units: K)
      7.1.1. Maximum value occurring anywhere in the core at BOL
      7.1.2. Maximum value occurring anywhere in the core at EOL
      7.1.3. Maximum value occurring anywhere in the core at any time during the operating cycle
   7.2. Pebble surface temperature
      7.2.1. Maximum value occurring anywhere in the core at BOL
      7.2.2. Maximum value occurring anywhere in the core at EOL
      7.2.3. Maximum value occurring anywhere in the core at any time during the operating cycle

8. Temperature reactivity coefficients. The perturbed state has "frozen" thermal hydraulics and the same nuclide concentrations as the reference state anywhere in the system. The local temperature of the system part (fuel, moderator, reflector) for which the temperature reactivity coefficient is to be calculated is increased by $\Delta T = 50$ K (k_{delta}), while the temperature of the remainder of the system is at the same temperature as in the reference state. The temperature reactivity coefficient (α) is subsequently calculated as:

$$\alpha = (1/\,k_{ref} - 1/\,k_{delta}\,)\,10^5\,/\,\Delta T \quad \text{(units: pcm/K)}$$

The following items should be calculated as function of time over the operating cycle, at least at BOL, MOL and EOL. The exact part of the system for which the coefficient is calculated should be indicated.

8.1. Temperature reactivity coefficients at Cold Zero Power (CZP, zero xenon) conditions (units: pcm/K). The reference state for this calculation is an isothermal reactor at 300 K (k_{ref}). The temperature reactivity coefficients should be calculated for:
8.1.1. Fuel compacts/pebbles
8.1.2. Moderator in the core cavity
8.1.3. Reflectors

8.2. Temperature reactivity coefficients at Hot Zero Power (HZP, zero xenon) conditions (unit: pcm/K). The reference state for this calculation is an isothermal reactor at nominal coolant inlet temperature (k_{ref}) (see item 1.14). The temperature reactivity coefficients should be calculated for:
8.2.1. Fuel compacts/pebbles
8.2.2. Moderator in the core cavity
8.2.3. Reflectors

8.3. Temperature reactivity coefficients at Hot Full Power (HFP or nominal, equilibrium xenon) conditions (units: pcm/K). The reference state for this calculation is the temperature distribution at nominal conditions (k_{ref}). The temperature reactivity coefficients should be calculated for:
8.3.1. Coated particles (per coated particle type)
8.3.2. Fuel compacts/pebbles
8.3.3. Moderator in the core cavity
8.3.4. Reflectors

8.4. Differences in reactivity (units: pcm) between:
8.4.1. CZP (zero xenon) state and HZP (zero xenon) state
8.4.2. CZP (zero xenon) state and HFP (equilibrium xenon) state

D.3 FILE FORMAT

The items mentioned above for a specific case should be send to the Work Package 3 manager in the form of an ASCII text file (one file per case) in which each of the items mentioned above is indicated, in the leftmost columns, by an identifier derived from the item number (format: “#<item number>#). Multiple values for the same item are put in consecutive lines, each preceded by the item indicator. E.g. the lines containing values for item 4.1 (“Amount and composition of fresh fuel loaded into the system for one operating cycle (per heavy metal nuclide) divided by the operating cycle length (units:kg/year)”) look like:

```
#4.1#     U235     <value>
#4.1#     U238     <value>
.
.
.
#4.1#     Pu239    <value>
```

This also holds for textual information (e.g. item 1.19). So effectively every line must be preceded with the appropriate item indicator. Any other comment should be preceded by “##” in the two leftmost columns. A full example of an output file, together with some further instructions, is given in [3] (also see Appendix E). The Unix ‘grep’ and ‘awk’ utilities will be used to extract data from this file (item sets 2 to 8) for further postprocessing and intercomparison.

D.4 ACTINIDES AND FISSION PRODUCTS UNDER CONSIDERATION

For items 3, 4 and 5 of Section D.2, values have to be calculated per nuclide: actinides (heavy metal) and fission products. The lists of nuclides to be taken into account are given in Table D.1 and 2. The fission products are selected on their relevance with respect to final disposal [D1]. The selection of the actinides is identical to the one employed in the EU 5FP project THORIUM [D2], also to facilitate intercomparison with other reactor types, such as LWRs.

Table D.1 List of selected fission products for intercomparison

Se-79	Sn-126
Rb-87	I-129
Sr-90	Cs-135
Zr-93	Cs-137
Mo-93	Sm-147
Nb-94	Sm-151
Tc-99	Eu-154
Pd-107	

Table D.2 List of selected actinides for intercomparison

Th-230	Pa-231	U-232	Np-237	Pu-238	Am-241	Cm-242
Th-232	Pa-233	U-233	Np-238	Pu-239	Am-242m	Cm-243
		U-234	Np-239	Pu-240	Am-243	Cm-244
		U-235		Pu-241		Cm-245
		U-236		Pu-242		
		U-238		Pu-243		
		U-239		Pu-244		

D.5 REFERENCES

[D1] Commissie Opberging te Land (OPLA), "Eindrapport Fase 1, Bijlage 1, Samenvatting van de Veiligheidsstudie", Ministry of Economic Affairs, the Netherlands, May 1989.

[D2] T. Bodewig *et al.*, "Report on the basic data for the reference core", Report Th5-DOC-005, EU 5FP project THORIUM, contract no. FIKI-CT-2000-00042, March 2002.

[D3] Sample output file "SAMPLE_FORMAT.20020620.txt", SINTER document HTR-N-02/06-S-3.1.1, June 2002; see Appendix E.

E SAMPLE OUTPUT FORMAT

Original document

(**Section E.1**) Sample output file “SAMPLE_FORMAT.20020620.txt”, Document HTR-N-02/06-S-3.1.1 in SINTER, June 2002 [9]

Additional remarks

Project partners are requested to put their calculated results in a for similar to this example, e.g. by replacing the dummy numbers by those actually calculated. The item identifiers (format: “#<item number>#”) should be kept intact to enable easy post-processing.

E.1 SAMPLE OUTPUT FILE "SAMPLE_FORMAT.20020620.TXT"

```
##--------------------------------------------------------------------
##
## SAMPLE_FORMAT.20020620.txt
##
## SINTER document no. HTR-N-02/06-S-3.1.1
##
## Status:  Draft for review
##
## Author:  J.C. Kuijper, NRG Petten
##
## Date:    24. June 2002
##
##--------------------------------------------------------------------
##
## This is a sample format for the ASCII output file
## containing the common output parameters for the
## designs and cases to be intercompared, as described
## in the "Definition of common output parameters"
## (document HTR-N-01/02-D-3.1.5).
##
## A line starting with a '##' contains comment.
##
## A line starting with '#n.m#' or '#n.m.l#' contains a data item
## to be supplied by the user (some dummy numbers are inserted in this
## example). The Unix 'grep' and 'awk' commands will be used to extract
## data from this file (item sets 2 to 8) for postprocessing and intercomparison.
##
## Rename the file to <organisation>_<date:YYYYMMDD>_<case ID number>.txt
## Example: NRG_20020620_1.txt
##
## The explanation of a specific item is usually given in the
## comment line(s) following the item. Please refer to the "Common
## ouput parameters" document (HTR-N-01/02-D-3.1.5, 20 June 2002)
## for the proper description of each data item.
##

## 0. Case identification and description.
##
#0.1# J.C. Kuijper
## Origin
#0.2# NRG
## Organisation
#0.3# 1
## Case number
#0.4# 20 June 2002
## Date
#0.5# PANTHERMIX
## Applied code system
#0.6# -
#0.6# -
#0.6# -
#0.6# -
#0.6# -
## References (arbitrary number of text lines)

## 1. General fuel/reactor/system specifications. This section is intended
##    as a complete description of the fuel, the reactor (system) and the applied
##    fuel loading and discharge scheme.
##
#1.1#
#1.1#
## System (part) under consideration (reactor, supercell, etc.)
## (arbitrary number of text lines)
#1.2#
#1.2#
## Main system dimensions (i.e. core diameter, core height, reflector dimensions, etc.)
## (arbitrary number of text lines)
#1.3# PuO2 particle:    Kernel            0.290 mm diameter
#1.3# PuO2 particle:    1st Carbon
#1.3# PuO2 particle:
#1.3# UO2 particle:     Kernel            0.50 mm diameter
#1.3# UO2 particle:     1st Carbon
#1.3# UO2 particle:
## Coated particle dimensions (kernel and coatings) (per coated particle type)
## (arbitrary number of text lines)
#1.4# PuO2 particle:    U235  9.9999
#1.4#
#1.4#
#1.4#
#1.4#
#1.4#
```

```
## Initial coated particle composition per nuclide per material zone (units: (barn cm)^-1)
## (arbitrary number of text lines; one line per nuclide per coated particle type; see
## Table 2; add extra nuclide names for impurities)
#1.5#
## Compact/pebble dimensions (arbitrary number of lines)
#1.6# C          9.9
#1.6#
#1.6#
## Compact/pebble composition per nuclide (outside coated particles; including impurities)
## (units: (barn cm)^-1) (arbitrary number of lines; one line per nuclide)
#1.7# C          9.9
#1.7#
#1.7#
## Block composition per nuclide (outside coated particles; including impurities)
## (units: (barn cm)^-1) (arbitrary number of lines; one line per nuclide)
#1.8# Type_1     10000
#1.8# Type_2     12000
#1.8#
## Number of coated particles per pebble/compact (of each coated particle type)
## (arbitrary number of lines; one line per particle type)
#1.9# 300.0
## Operating cycle length (units: full power days)
#1.10# 9.9
## Reload stop duration (units: days) (may be 0 in case of continuous reload,
## in which case EOL coincides with the end of the operating cycle)
#1.11# 999.9
## Nominal reactor power (units: MW)
#1.12# 1.0
## Capacity factor (units: -)
#1.13# 1.0
## Number of fuel batches (batch wise reload only) (units: -)
#1.14# 999.9
## Nominal coolant inlet temperature (units: K)
#1.15# 99999.9
## Nominal coolant inlet pressure (units: Pa)
#1.16# 9999.9
## Nominal coolant outlet temperature at nominal (Hot Full Power, HFP) conditions (units: K)
#1.17# 99999.9
## Nominal coolant outlet pressure at nominal (Hot Full Power, HFP) conditions (units: Pa)
#1.18# 99.9
## Nominal coolant mass flow (unit: kg/s)
#1.19# Text line
#1.19# Text line
#1.19# Text line
## Description of fuel cycle strategy and other relevant information on the specific case
## (arbitrary number of text lines).

## 2. Rating and power density
##
## 2.1. Power produced per coated particle (per coated partcile type) (units: W):
#2.1.1# 9.9
## Maximum value occurring anywhere in the core at any time during the operating cycle
#2.1.2# 0.0 9.9
#2.1.2# 1.0 9.9
#2.1.2# 2.0 9.9
#2.1.2# 5.0 9.9
#2.1.2# 8.0 9.9
## Maximum value occurring anywhere in the core as function of time over the operating cycle
## (pairs of numbers: time (units: days), power (units: W)) (arbitrary number of lines)
## 2.2. Power produced per compact/pebble (units: W)
#2.2.1# 99.9
## Maximum value occurring anywhere in the core at any time during the operating cycle
#2.2.2# 0.0 9.9
#2.2.2# 2.0 9.9
#2.2.2# 4.0 9.9
#2.2.2# 6.0 9.9
#2.2.2# 8.0 9.9
#2.2.2# 9.0 9.9
## Maximum value occurring anywhere in the core as function of time over the operating cycle
## (pairs of numbers: time (units: days), power (units: W)) (arbitrary number of lines)
## 2.3. Power produced per unit heavy metal mass (units: W/kg)
#2.3.1# 9.9
## Maximum value occurring anywhere in the core at any time during the operating cycle
#2.3.2# 0.0 99.9
#2.3.2# 2.0 99.9
#2.3.2# 5.0 99.9
#2.3.2# 6.0 99.9
#2.3.2# 7.0 99.9
#2.3.2# 9.0 99.9
## Maximum value anywhere in the core as function of time over the operating cycle
## (pairs of numbers: time (units: days), power per unit heavy metal mass (units: W/kg))
## (arbitrary number of lines)
## 2.4. Power density in the core  (units: W/m^3)
#2.4.1# 999.9
## Maximum value occurring anywhere in the core at any time during the operating cycle
#2.4.2# 0.0 999.9
```

```
#2.4.2# 2.0 999.9
#2.4.2# 3.0 999.9
#2.4.2# 9.0 999.9
## Maximum value occurring anywhere in the core as function of time over the operating cycle
## (pairs of numbers: time (units: days), power density (units: W/m^3)) (arbitrary number of lines)

## 3. Core inventory
##
## 3.1. Amount of each of the heavy metal isotopes present in the core (units: kg)
#3.1.1#     AM241 9999.9
#3.1.1#     AM242M      9999.9
#3.1.1#     AM243 9999.9
#3.1.1#     CM242 9999.9
#3.1.1#     CM243 9999.9
#3.1.1#     CM244 9999.9
#3.1.1#     CM245 9999.9
#3.1.1#     NP237 9999.9
#3.1.1#     NP238 9999.9
#3.1.1#     NP239 9999.9
#3.1.1#     PA231 9999.9
#3.1.1#     PA233 9999.9
#3.1.1#     PU238 9999.9
#3.1.1#     PU239 9999.9
#3.1.1#     PU240 9999.9
#3.1.1#     PU241 9999.9
#3.1.1#     PU242 9999.9
#3.1.1#     PU243 9999.9
#3.1.1#     PU244 9999.9
#3.1.1#     TH230 9999.9
#3.1.1#     TH232 9999.9
#3.1.1#     U232  9999.9
#3.1.1#     U233  9999.9
#3.1.1#     U234  9999.9
#3.1.1#     U235  9999.9
#3.1.1#     U236  9999.9
#3.1.1#     U238  9999.9
#3.1.1#     U239  9999.9
## At BOL (arbitrary number of lines; see Table 2)
#3.1.2#     AM241 9999.9
#3.1.2#     AM242M      9999.9
#3.1.2#     AM243 9999.9
#3.1.2#     CM242 9999.9
#3.1.2#     CM243 9999.9
#3.1.2#     CM244 9999.9
#3.1.2#     CM245 9999.9
#3.1.2#     NP237 9999.9
#3.1.2#     NP238 9999.9
#3.1.2#     NP239 9999.9
#3.1.2#     PA231 9999.9
#3.1.2#     PA233 9999.9
#3.1.2#     PU238 9999.9
#3.1.2#     PU239 9999.9
#3.1.2#     PU240 9999.9
#3.1.2#     PU241 9999.9
#3.1.2#     PU242 9999.9
#3.1.2#     PU243 9999.9
#3.1.2#     PU244 9999.9
#3.1.2#     TH230 9999.9
#3.1.2#     TH232 9999.9
#3.1.2#     U232  9999.9
#3.1.2#     U233  9999.9
#3.1.2#     U234  9999.9
#3.1.2#     U235  9999.9
#3.1.2#     U236  9999.9
#3.1.2#     U238  9999.9
#3.1.2#     U239  9999.9
## At MOL (arbitrary number of lines; see Table 2)
#3.1.3#     AM241 9999.9
#3.1.3#     AM242M      9999.9
#3.1.3#     AM243 9999.9
#3.1.3#     CM242 9999.9
#3.1.3#     CM243 9999.9
#3.1.3#     CM244 9999.9
#3.1.3#     CM245 9999.9
#3.1.3#     NP237 9999.9
#3.1.3#     NP238 9999.9
#3.1.3#     NP239 9999.9
#3.1.3#     PA231 9999.9
#3.1.3#     PA233 9999.9
#3.1.3#     PU238 9999.9
#3.1.3#     PU239 9999.9
#3.1.3#     PU240 9999.9
#3.1.3#     PU241 9999.9
#3.1.3#     PU242 9999.9
#3.1.3#     PU243 9999.9
#3.1.3#     PU244 9999.9
```

```
#3.1.3#     TH230 9999.9
#3.1.3#     TH232 9999.9
#3.1.3#     U232  9999.9
#3.1.3#     U233  9999.9
#3.1.3#     U234  9999.9
#3.1.3#     U235  9999.9
#3.1.3#     U236  9999.9
#3.1.3#     U238  9999.9
#3.1.3#     U239  9999.9
## At EOL (arbitrary number of lines; see Table 2)
## 3.2. Fissile Pu fraction, i.e. amount of (239Pu and 241Pu) divided by the total
##      amount of Pu (units: -) (this can be derived from 3.1)
#3.2.1# 0.99
## At BOL
#3.2.2# 0.99
## At MOL
#3.2.3# 0.99
## At EOL

## 4. Fuel (actinide) consumption, actinide and fission product production and
##    discharge burnup at nominal conditions. A list of  nuclides under consideration
##    is presented in section 3 (Table 1 and Table 2).
##
#4.1# AM241 99.9
#4.1# AM242M      99.9
#4.1# AM243 99.9
#4.1# CM242 99.9
#4.1# CM243 99.9
#4.1# CM244 99.9
#4.1# CM245 99.9
#4.1# NP237 99.9
#4.1# NP238 99.9
#4.1# NP239 99.9
#4.1# PA231 99.9
#4.1# PA233 99.9
#4.1# PU238 99.9
#4.1# PU239 99.9
#4.1# PU240 99.9
#4.1# PU241 99.9
#4.1# PU242 99.9
#4.1# PU243 99.9
#4.1# PU244 99.9
#4.1# TH230 99.9
#4.1# TH232 99.9
#4.1# U232  99.9
#4.1# U233  99.9
#4.1# U234  99.9
#4.1# U235  99.9
#4.1# U236  99.9
#4.1# U238  99.9
#4.1# U239  99.9
#4.1# CS135 00.0
#4.1# CS137 00.0
#4.1# EU154 00.0
#4.1# I129  00.0
#4.1# MO93  00.0
#4.1# NB94  00.0
#4.1# PD107 00.0
#4.1# RB87  00.0
#4.1# SE79  00.0
#4.1# SM147 00.0
#4.1# SM151 00.0
#4.1# SN126 00.0
#4.1# SR90  00.0
#4.1# TC99  00.0
#4.1# ZR93  00.0
## Amount and composition of fresh fuel loaded into the system for one operating cycle
## (per heavy metal nuclide) divided by the operating cycle length (units:kg/year)
## (arbitrary number of lines; one line per nuclide)
#4.2# AM241 99.9
#4.2# AM242M      99.9
#4.2# AM243 99.9
#4.2# CM242 99.9
#4.2# CM243 99.9
#4.2# CM244 99.9
#4.2# CM245 99.9
#4.2# NP237 99.9
#4.2# NP238 99.9
#4.2# NP239 99.9
#4.2# PA231 99.9
#4.2# PA233 99.9
#4.2# PU238 99.9
#4.2# PU239 99.9
#4.2# PU240 99.9
#4.2# PU241 99.9
#4.2# PU242 99.9
```

```
#4.2# PU243 99.9
#4.2# PU244 99.9
#4.2# TH230 99.9
#4.2# TH232 99.9
#4.2# U232  99.9
#4.2# U233  99.9
#4.2# U234  99.9
#4.2# U235  99.9
#4.2# U236  99.9
#4.2# U238  99.9
#4.2# U239  99.9
#4.2# CS135 99.0
#4.2# CS137 99.0
#4.2# EU154 99.0
#4.2# I129  99.0
#4.2# MO93  99.0
#4.2# NB94  99.0
#4.2# PD107 99.0
#4.2# RB87  99.0
#4.2# SE79  99.0
#4.2# SM147 99.0
#4.2# SM151 99.0
#4.2# SN126 99.0
#4.2# SR90  99.0
#4.2# TC99  99.0
#4.2# ZR93  99.0
## Amount and composition of fuel discharged from (and not reloaded into) the system for one
## operating cycle (per heavy metal and fission product nuclide) divided by the operating cycle
## length (units: kg/year) (arbitrary number of lines; one line per nuclide)
#4.3# AM241 99.9
#4.3# AM242M      99.9
#4.3# AM243 99.9
#4.3# CM242 99.9
#4.3# CM243 99.9
#4.3# CM244 99.9
#4.3# CM245 99.9
#4.3# NP237 99.9
#4.3# NP238 99.9
#4.3# NP239 99.9
#4.3# PA231 99.9
#4.3# PA233 99.9
#4.3# PU238 99.9
#4.3# PU239 99.9
#4.3# PU240 99.9
#4.3# PU241 99.9
#4.3# PU242 99.9
#4.3# PU243 99.9
#4.3# PU244 99.9
#4.3# TH230 99.9
#4.3# TH232 99.9
#4.3# U232  99.9
#4.3# U233  99.9
#4.3# U234  99.9
#4.3# U235  99.9
#4.3# U236  99.9
#4.3# U238  99.9
#4.3# U239  99.9
#4.3# CS135 99.0
#4.3# CS137 99.0
#4.3# EU154 99.0
#4.3# I129  99.0
#4.3# MO93  99.0
#4.3# NB94  99.0
#4.3# PD107 99.0
#4.3# RB87  99.0
#4.3# SE79  99.0
#4.3# SM147 99.0
#4.3# SM151 99.0
#4.3# SN126 99.0
#4.3# SR90  99.0
#4.3# TC99  99.0
#4.3# ZR93  99.0
## Balance of heavy metal and fission products, i.e. the difference between corresponding items
## 4.1 and 4.2, divided by nominal thermal power times capacity factor (units: kg/MWd)
## (same number of lines as for item 4.2; one line per nuclide)
##
## 4.4 Attained discharge burnup of the fuel (units: MWd/kg) (for each fuel type)
#4.4.1#     Fuel_type_1 99.99
#4.4.1#     Fuel_type_2 99.99
#4.4.1#     Fuel_type_3 99.99
## Minimum value (arbitrary number of lines; one line per fuel type;
## indicate fuel type by a single word, which may contain underscores)
#4.4.2#     Fuel_type_1 99.99
#4.4.2#     Fuel_type_2 99.99
#4.4.2#     Fuel_type_3 99.99
## Average value (one line per fuel type)
```

```
#4.4.3#     Fuel_type_1 99.99
#4.4.3#     Fuel_type_2 99.99
#4.4.3#     Fuel_type_3 99.99
## Maximum value (one line per fuel type)

## 5. Reaction rates at nominal conditions
##
## 5.1 Neutron induced fission rate per heavy metal nuclide in the entire system (units: s^-1)
#5.1.1#     AM241 9.9999E99
#5.1.1#     AM242M      9.9999E99
#5.1.1#     AM243 9.9999E99
#5.1.1#     CM242 9.9999E99
#5.1.1#     CM243 9.9999E99
#5.1.1#     CM244 9.9999E99
#5.1.1#     CM245 9.9999E99
#5.1.1#     NP237 9.9999E99
#5.1.1#     NP238 9.9999E99
#5.1.1#     NP239 9.9999E99
#5.1.1#     PA231 9.9999E99
#5.1.1#     PA233 9.9999E99
#5.1.1#     PU238 9.9999E99
#5.1.1#     PU239 9.9999E99
#5.1.1#     PU240 9.9999E99
#5.1.1#     PU241 9.9999E99
#5.1.1#     PU242 9.9999E99
#5.1.1#     PU243 9.9999E99
#5.1.1#     PU244 9.9999E99
#5.1.1#     TH230 9.9999E99
#5.1.1#     TH232 9.9999E99
#5.1.1#     U232  9.9999E99
#5.1.1#     U233  9.9999E99
#5.1.1#     U234  9.9999E99
#5.1.1#     U235  9.9999E99
#5.1.1#     U236  9.9999E99
#5.1.1#     U238  9.9999E99
#5.1.1#     U239  9.9999E99
## At BOL (arbitrary number of lines; one line per heavy metal nuclide, see Table 2)
#5.1.2#     AM241 9.9999E99
#5.1.2#     AM242M      9.9999E99
#5.1.2#     AM243 9.9999E99
#5.1.2#     CM242 9.9999E99
#5.1.2#     CM243 9.9999E99
#5.1.2#     CM244 9.9999E99
#5.1.2#     CM245 9.9999E99
#5.1.2#     NP237 9.9999E99
#5.1.2#     NP238 9.9999E99
#5.1.2#     NP239 9.9999E99
#5.1.2#     PA231 9.9999E99
#5.1.2#     PA233 9.9999E99
#5.1.2#     PU238 9.9999E99
#5.1.2#     PU239 9.9999E99
#5.1.2#     PU240 9.9999E99
#5.1.2#     PU241 9.9999E99
#5.1.2#     PU242 9.9999E99
#5.1.2#     PU243 9.9999E99
#5.1.2#     PU244 9.9999E99
#5.1.2#     TH230 9.9999E99
#5.1.2#     TH232 9.9999E99
#5.1.2#     U232  9.9999E99
#5.1.2#     U233  9.9999E99
#5.1.2#     U234  9.9999E99
#5.1.2#     U235  9.9999E99
#5.1.2#     U236  9.9999E99
#5.1.2#     U238  9.9999E99
#5.1.2#     U239  9.9999E99
## At MOL (same number of lines as for item 5.1.1; one line per heavy metal nuclide, see Table 2)
#5.1.3#     AM241 9.9999E99
#5.1.3#     AM242M      9.9999E99
#5.1.3#     AM243 9.9999E99
#5.1.3#     CM242 9.9999E99
#5.1.3#     CM243 9.9999E99
#5.1.3#     CM244 9.9999E99
#5.1.3#     CM245 9.9999E99
#5.1.3#     NP237 9.9999E99
#5.1.3#     NP238 9.9999E99
#5.1.3#     NP239 9.9999E99
#5.1.3#     PA231 9.9999E99
#5.1.3#     PA233 9.9999E99
#5.1.3#     PU238 9.9999E99
#5.1.3#     PU239 9.9999E99
#5.1.3#     PU240 9.9999E99
#5.1.3#     PU241 9.9999E99
#5.1.3#     PU242 9.9999E99
#5.1.3#     PU243 9.9999E99
#5.1.3#     PU244 9.9999E99
#5.1.3#     TH230 9.9999E99
```

```
#5.1.3#     TH232 9.9999E99
#5.1.3#     U232  9.9999E99
#5.1.3#     U233  9.9999E99
#5.1.3#     U234  9.9999E99
#5.1.3#     U235  9.9999E99
#5.1.3#     U236  9.9999E99
#5.1.3#     U238  9.9999E99
#5.1.3#     U239  9.9999E99
## At EOL (same number of lines as for item 5.1.1; one line per heavy metal nuclide, see Table 2)
##
## 5.2 Neutron absorption rate for all (heavy metal, fission product and possibly burnable poison)
##     nuclides present in the kernels of all coated particles (units: s^-1) (per nuclide)
#5.2.1#     AM241 9.9999E99
#5.2.1#     AM242M      9.9999E99
#5.2.1#     AM243 9.9999E99
#5.2.1#     CM242 9.9999E99
#5.2.1#     CM243 9.9999E99
#5.2.1#     CM244 9.9999E99
#5.2.1#     CM245 9.9999E99
#5.2.1#     NP237 9.9999E99
#5.2.1#     NP238 9.9999E99
#5.2.1#     NP239 9.9999E99
#5.2.1#     PA231 9.9999E99
#5.2.1#     PA233 9.9999E99
#5.2.1#     PU238 9.9999E99
#5.2.1#     PU239 9.9999E99
#5.2.1#     PU240 9.9999E99
#5.2.1#     PU241 9.9999E99
#5.2.1#     PU242 9.9999E99
#5.2.1#     PU243 9.9999E99
#5.2.1#     PU244 9.9999E99
#5.2.1#     TH230 9.9999E99
#5.2.1#     TH232 9.9999E99
#5.2.1#     U232  9.9999E99
#5.2.1#     U233  9.9999E99
#5.2.1#     U234  9.9999E99
#5.2.1#     U235  9.9999E99
#5.2.1#     U236  9.9999E99
#5.2.1#     U238  9.9999E99
#5.2.1#     U239  9.9999E99
#5.2.1#
## At BOL (arbitrary number of lines: one line per nuclide; add extra lines to describe
## e.g. burnable poison nuclides not present in the standard lists in Table 1 and Table 2)
#5.2.2#     AM241 9.9999E99
#5.2.2#     AM242M      9.9999E99
#5.2.2#     AM243 9.9999E99
#5.2.2#     CM242 9.9999E99
#5.2.2#     CM243 9.9999E99
#5.2.2#     CM244 9.9999E99
#5.2.2#     CM245 9.9999E99
#5.2.2#     NP237 9.9999E99
#5.2.2#     NP238 9.9999E99
#5.2.2#     NP239 9.9999E99
#5.2.2#     PA231 9.9999E99
#5.2.2#     PA233 9.9999E99
#5.2.2#     PU238 9.9999E99
#5.2.2#     PU239 9.9999E99
#5.2.2#     PU240 9.9999E99
#5.2.2#     PU241 9.9999E99
#5.2.2#     PU242 9.9999E99
#5.2.2#     PU243 9.9999E99
#5.2.2#     PU244 9.9999E99
#5.2.2#     TH230 9.9999E99
#5.2.2#     TH232 9.9999E99
#5.2.2#     U232  9.9999E99
#5.2.2#     U233  9.9999E99
#5.2.2#     U234  9.9999E99
#5.2.2#     U235  9.9999E99
#5.2.2#     U236  9.9999E99
#5.2.2#     U238  9.9999E99
#5.2.2#     U239  9.9999E99
#5.2.2#
## At MOL (same number of lines as for item 5.2.1)
#5.2.3#     AM241 9.9999E99
#5.2.3#     AM242M      9.9999E99
#5.2.3#     AM243 9.9999E99
#5.2.3#     CM242 9.9999E99
#5.2.3#     CM243 9.9999E99
#5.2.3#     CM244 9.9999E99
#5.2.3#     CM245 9.9999E99
#5.2.3#     NP237 9.9999E99
#5.2.3#     NP238 9.9999E99
#5.2.3#     NP239 9.9999E99
#5.2.3#     PA231 9.9999E99
#5.2.3#     PA233 9.9999E99
#5.2.3#     PU238 9.9999E99
```

```
#5.2.3#     PU239 9.9999E99
#5.2.3#     PU240 9.9999E99
#5.2.3#     PU241 9.9999E99
#5.2.3#     PU242 9.9999E99
#5.2.3#     PU243 9.9999E99
#5.2.3#     PU244 9.9999E99
#5.2.3#     TH230 9.9999E99
#5.2.3#     TH232 9.9999E99
#5.2.3#     U232  9.9999E99
#5.2.3#     U233  9.9999E99
#5.2.3#     U234  9.9999E99
#5.2.3#     U235  9.9999E99
#5.2.3#     U236  9.9999E99
#5.2.3#     U238  9.9999E99
#5.2.3#     U239  9.9999E99
#5.2.3#
## At EOL (same number of lines as for item 5.2.1)
##
## 5.3 Neutron absorption rate in all other material in the core cavity (units: s^-1)
##     (per nuclide, including impurities and/or burnable poison if present)
#5.3.1# B10 9.9999E99
#5.3.1#
#5.3.1#
#5.3.1# SI28      9.9999E99
#5.3.1#
#5.3.1#
#5.3.1#
#5.3.1#
#5.3.1#
#5.3.1#
#5.3.1#
## At BOL (arbitrary number of lines: one line per nuclide; add extra lines to describe
## e.g. burnable poison nuclides not present in the standard list)
#5.3.2#
#5.3.2#
#5.3.2#
## At MOL (same number of lines as for item 5.3.1: one line per nuclide; add extra lines to describe
## e.g. burnable poison nuclides not present in the standard list)
#5.3.3#
#5.3.3#
#5.3.3#
## At EOL (same number of lines as for item 5.3.1: one line per nuclide; add extra lines to describe
## e.g. burnable poison nuclides not present in the standard list)
##
## 5.4 Net neutron leakage rate from the core cavity (units: s^-1) (integrated over all neutron
energies)
#5.4.1#
## At BOL
#5.4.2#
## At MOL
#5.4.3#
## At EOL

## 6. Fast and thermal neutron flux (fluence rate) and fluence measures at nominal conditions
##
## 6.1 Thermal flux below 1.86 eV (units: m^-2s^-1). The items listed below should be calculated at
BOL,
##     MOL and EOL.
#6.1.1# 9.9999E99 9.9999E99   9.9999E99
## Average value in the core (one line containing BOL, MOL and EOL values)
#6.1.2# 9.9999E99 9.9999E99   9.9999E99
## Peak value in the core (one line containing BOL, MOL and EOL values)
#6.1.3# 9.9999E99 9.9999E99   9.9999E99
## Average value in the reflector (one line containing BOL, MOL and EOL values)
#6.1.4# 9.9999E99 9.9999E99   9.9999E99
## Peak value in the reflector (one line containing BOL, MOL and EOL values)
#6.1.5# 0.0 9.9999E99       9.9999E99       9.9999E9
#6.1.5# 0.50      9.9999E99       9.9999E99       9.9999E9
#6.1.5#
## Axial distribution of the thermal flux along the centre axis
## (arbitrary number of lines; one line per axial position; each line contains
## the axial position above core bottom (units: m), BOL, MOL and EOL values)
#6.1.6# 0.0 9.9999E99       9.9999E99       9.9999E9
#6.1.6# 0.30      9.9999E99       9.9999E99       9.9999E9
#6.1.6#
## Radial distribution of the thermal flux at half core height
## (arbitrary number of lines; one line per radial position; each line contains
## the distance to centre line (units: m), BOL, MOL and EOL values)
##
## 6.2 59Co(n,gamma) reaction rate of a 10^-10 (barn cm)^-1 trace of 59Co in all materials in the
core and
##     reflector. This is a measure of the thermal flux below ~1 eV, which is independent of the
energy
##     group structure employed in the calculations. The items listed below should be calculated at
##     BOL, MOL and EOL and presented in the same way as for item set 6.1.
#6.2.1# 9.9999E99 9.9999E99   9.9999E99
```

```
## Total reaction rate in the core (units: s-1)
#6.2.2# 9.9999E99 9.9999E99   9.9999E99
## Total reaction rate in the reflector (units: s-1)
#6.2.3# 9.9999E99 9.9999E99   9.9999E99
## Peak value of the reaction rate density in the core (units: s-1m-3)
#6.2.4# 9.9999E99 9.9999E99   9.9999E99
## Peak value of the reaction rate density in the reflector (units: s-1m-3)
#6.2.5# 0.0 9.9999E99   9.9999E99   9.9999E99
#6.2.5# 0.50      9.9999E99   9.9999E99   9.9999E99
#6.2.5#
## Axial distribution of the reaction rate density along the centre axis (units: s-1m-3)
#6.2.6# 0.0 9.9999E99   9.9999E99   9.9999E99
#6.2.6# 0.30      9.9999E99   9.9999E99   9.9999E99
#6.2.6#
## Radial distribution of the reaction rate density at half core height (units: s-1m-3)
##
## 6.3 Fast flux (fluence rate) above 0.1 MeV (units: m-2s-1). The items listed below should be
##     calculated at BOL, MOL and EOL and presented in the same way as for item set 6.1.
#6.3.1# 9.9999E99 9.9999E99   9.9999E99
## Average value in the core (one line containing BOL, MOL and EOL values)
#6.3.2# 9.9999E99 9.9999E99   9.9999E99
## Peak value in the core (one line containing BOL, MOL and EOL values)
#6.3.3# 9.9999E99 9.9999E99   9.9999E99
## Average value in the reflector (one line containing BOL, MOL and EOL values)
#6.3.4# 9.9999E99 9.9999E99   9.9999E99
## Peak value in the reflector (one line containing BOL, MOL and EOL values)
#6.3.5# 0.0 9.9999E99       9.9999E99       9.9999E9
#6.3.5# 0.50      9.9999E99       9.9999E99       9.9999E9
#6.3.5#
## Axial distribution of the fast flux along the centre axis
## (arbitrary number of lines; one line per axial position; each line contains
## the axial position above core bottom (units: m), BOL, MOL and EOL values)
#6.3.6# 0.0 9.9999E99       9.9999E99       9.9999E9
#6.3.6# 0.30      9.9999E99       9.9999E99       9.9999E9
#6.3.6#
## Radial distribution of the fast flux at half core height
## (arbitrary number of lines; one line per radial position; each line contains
## the distance to centre line (units: m), BOL, MOL and EOL values)
##
## 6.4 58Ni(n,p) reaction rate of a 10^-10 (barn cm)^-1 trace of 58Ni in all materials in the core
and
##     reflector. This is a measure of the fast flux above ~2 MeV, which is independent of the
energy
##     group structure employed in the calculations. The items listed below should be calculated at
##     BOL, MOL and EOL and presented in the same way as for item set 6.1.
#6.4.1# 9.9999E99 9.9999E99   9.9999E99
## Total reaction rate in the core (units: s-1)
#6.4.2# 9.9999E99 9.9999E99   9.9999E99
## Total reaction rate in the reflector (units: s-1)
#6.4.3# 9.9999E99 9.9999E99   9.9999E99
## Peak value of the reaction rate density in the core (units: s-1m-3)
#6.4.4# 9.9999E99 9.9999E99   9.9999E99
## Peak value of the reaction rate density in the reflector (units: s-1m-3)
#6.4.5# 0.0 9.9999E99   9.9999E99   9.9999E99
#6.4.5# 0.50      9.9999E99   9.9999E99   9.9999E99
#6.4.5#
## Axial distribution of the reaction rate density along the centre axis (units: s-1m-3)
#6.4.6# 0.0 9.9999E99   9.9999E99   9.9999E99
#6.4.6# 0.30      9.9999E99   9.9999E99   9.9999E99
#6.4.6#
## Radial distribution of the reaction rate density at half core height (units: s-1m-3)
##
## 6.5 Fast fluence above 0.1 MeV of discharged fuel (kernel, coatings, matrix) (units: m-2)
#6.5.1# 9.9999E99
## Minimum value
#6.5.2# 9.9999E99
## Average value
#6.5.3# 9.9999E99
## Maximum value

## 7. Temperatures at nominal conditions
##
## 7.1 Coated particle temperature (units: K)
#7.1.1# 999.9
## Maximum value occurring anywhere in the core at BOL
#7.1.2# 999.9
## Maximum value occurring anywhere in the core at EOL
#7.1.3# 999.9
## Maximum value occurring anywhere in the core at any time during the operating cycle
##
##7.2. Pebble surface temperature (units: K)
#7.2.1# 999.9
## Maximum value occurring anywhere in the core at BOL
#7.2.2# 999.9
## Maximum value occurring anywhere in the core at EOL
#7.2.3# 999.9
```

```
## Maximum value occurring anywhere in the core at any time during the operating cycle

## 8. Temperature reactivity coefficients. The following items should be calculated
##    as function of time over the operating cycle, at least at BOL, MOL and EOL.
##    The exact part of the system for which the coefficient is calculated should be
##    indicated in additional comment lines (so starting with '##').
##
## 8.1 Temperature reactivity coefficients at Cold Zero Power (CZP, zero xenon) conditions (units:
##     pcm/K). The reference state for this calculation is an isothermal reactor at 300 K (kref).
##     The temperature reactivity coefficients should be calculated for:
#8.1.1# 999.9
## Fuel compacts/pebbles
#8.1.2# 999.9
## Moderator in the core cavity (e.g. central rfelector)
#8.1.3# 999.9
## (Outer) reflectors
##
## 8.2 Temperature reactivity coefficients at Hot Zero Power (HZP, zero xenon) conditions (unit:
##     pcm/K). The reference state for this calculation is an isothermal reactor at nominal coolant
inlet
##     temperature (kref) (see item 1.14). The temperature reactivity coefficients should be
calculated
##     for:
#8.2.1# 999.9
## Fuel compacts/pebbles
#8.2.2# 999.9
## Moderator in the core cavity
#8.2.3# 999.9
## Reflectors
##
## 8.3 Temperature reactivity coefficients at Hot Full Power (HFP or nominal, equilibrium xenon)
##     conditions (units: pcm/K). The reference state for this calculation is the temperature
distribution
##     at nominal conditions (kref). The temperature reactivity coefficients should be calculated
for:
#8.3.1# Type_1    999.9
## Coated particles (arbitrary number of lines; one line per coated particle type;
## line contains particle type and temperature reactivity coefficient;
## indicate particle type by a single word, which may contain underscores)
#8.3.2# 999.9
## Fuel compacts/pebbles
#8.3.3# 999.9
## Moderator in the core cavity (central reflector)
#8.3.4# 999.9
## Reflectors
##
## 8.4 Differences in reactivity (units: pcm) between:
#8.4.1# -9999
## CZP (zero xenon) state and HZP (zero xenon) state
#8.4.2# -9999
## CZP (zero xenon) state and HFP (equilibrium xenon) state
```

F HTR PU CELL BURNUP BENCHMARK

Original document

(**Sections F.1 - F.3**) H.J. Ruetten & J.C. Kuijper, "Plutonium (1st and 2nd generation) cell burnup benchmark specification", Document HTR-N1-02/06-S-3.1.1 in SINTER, 11. March 2003, NRG report 20780/03.52483/C [10].

Additional remarks

-

F.1 INTRODUCTION

This document contains the specification of the "Plutonium (*1st* and *2nd generation*) cell burnup benchmark in the framework of the "HTR-N1" contract [F1]. It is based upon the original specifications by H.J. Ruetten [F2], additions/modifications agreed upon by the HTR-N/WP3 partners at the WP3 meeting of 28. May 2002 in Pisa, Italy [F3] and additional specifications stated in the E-mail of J.C. Kuijper of 23. December 2003 [F6]. The main modifications with respect to the original specifications concern the plutonium vectors to be used, the heavy metal mass per fuel element for *1st generation* Pu and an explicit list of (heavy metal and fission product) nuclides to be tracked. A specific format definition for the items to be calculated will not be given as the number of these items is quite limited.

F.2 BENCHMARK DEFINITION

For simplicity the benchmark concerns only a spherical ("pebble") fuel element containing coated fuel particles. The neutronic boundary condition is assumed to be "white", i.e. isotropic reflection from the outer boundary of the pebble. Although this is not entirely representative for a full scale pebble bed HTR it is expected to serve the purpose as a basis for intercomparison of codes and data for the reactor physics analysis of an HTR fuel at high burnup. More specifically k_∞ will drop below 1 at high values of the irradiation. This is not considered to be a problem, as in a real pebble bed HTR such a pebble at high burnup will be surrounded by "driver" fuel at lower burnup so that the criticality of the reactor can be maintained. The fuel element parameters and isotopic compositions correspond to those of the PuO_2 coated particles defined in the "Definition of reference coated particles and plutonium compositions (1st and 2nd generation Pu)" [F4] (also see Appendix A).

2.1 Fuel element parameters

The main parameters of the fuel elements employed in this benchmark are the following:

Diameter of fuel element (FE)	6.0 cm
Diameter of central fuel zone of FE	5.0 cm
Graphite density	1.75 g/cm^3
Amount of Pu	1.0 g per FE (*1st generation* Pu)
	1.5 g per FE (*2nd generation* Pu)
	3.0 g per FE (*2nd generation* Pu)

2.2 Coated particle parameters

The coated fuel particles consist of a fuel kernel containing the PuO_2 fuel surrounded by coatings. These coated particles are embedded in a graphite matrix (density: 1.75 g/cm^3) in the central fuel zone of the FE. The main parameters of the coated fuel particles are the following:

PuO_2-density in the kernel	10.4 g/cm^3
Kernel diameter	0.24 mm
Coating layer materials (inner to outer)	C / C / SiC / C
Coating thickness (inner to outer)	95 / 40 / 35 / 40 μm
Coating density (inner to outer)	1.05 / 1.90 / 3.18 /1.90 g/cm^3

2.3 Plutonium isotopic compositions

The isotopic compositions of the *1st* and *2nd* generation plutonium are as specified in [F4]:

Isotope	***1st generation* (original) (A)**	***1st generation* (alternative) (B)**	***2nd generation* (C)**
Unit	**weight %**	**weight %**	**weight %**
^{238}Pu	1	**2.59**	**4.9**
^{239}Pu	62	**53.85**	**26.9**
^{240}Pu	24	**23.66**	**34.3**
^{241}Pu	8	**13.13**	**15.3**
^{242}Pu	5	**6.78**	**18.6**
^{241}Am	-	**-**	**-**

As agreed at the WP3 meeting of 28. May 2002 [3] the ***1st generation*** (alternative) (**B**) and ***2nd generation*** (**C**) Pu compositions (both!) will be the reference compositions for the “Pu cell burnup benchmark”. However, the original *1st generation* reference composition (A) can be regarded as a variation on the *1st generation* base case (to be analysed by one partner). Note that the *2nd generation* plutonium vector given above is different from the one in the original specification (viz. 238/239/240/241/242 = 5/36/35/10/14 atom %) [2]. Also this composition can be regarded as a variation on the *2nd generation* base case.

2.4 General parameters

Power per FE (constant during burnup)	1.0 kW
Average temperature of 5 cm central fuel zone (i.e. kernel, coatings and matrix)	800 degr. C
Average temperature of 0.5 cm graphite outer zone	750 degr. C
Final burnup	800 MWd/kgHM
Irradiation time	800 full power days (1.0 g per FE) (cases “**A**” and ”**B**”) 1200 full power days (1.5 g per FE) (case “**C1**”) 2400 full power days (3.0 g per FE) (case “**C2**”)

2.5 Items to be calculated

The burnup history of the fuel at the defined constant power should be calculated for the selected Pu composition, not using any neutron poison, or any other means, for reactivity control. For a burnup of **0, 100, 400, 600 and 800 MWd/kgHM** the following items should be reported:

- Neutron multiplication of FE (k_∞) **[-]**
- Isotopic (heavy metal and fission products) composition of the fuel kernel (see next table for list of nuclides) **[10^{24}/cm^3]**
- Neutron flux (collapsed to 1 group) **[$s^{-1}cm^{-2}$]**
- 1-group microscopic absorption cross sections for each of the considered isotopes **[barn]**
- 1-group microscopic fission cross sections for each of the considered isotopes **[barn]**
- Total fission rate **[s^{-1}]**

The nuclides to be considered in the isotopic compositions (and the 1-group microscopic cross sections) are the listed below (also see [F5]). It is understood that some of the nuclides mentioned are not explicitly calculated by some of the code systems employed by the HTR-N1 WP3 partners.

Heavy metal		**Fission products**	
Pu-238	Am-241	Se-79	Sn-126
Pu-239	Am-242m	Rb-87	I-129
Pu-240	Am-243	Sr-90	Cs-135
Pu-241	Cm-242	Zr-93	Cs-137
Pu-242	Cm-243	Mo-93	Sm-147
Pu-243	Cm-244	Nb-94	Sm-151
Pu-244	Cm-245	Tc-99	Eu-154
		Pd-107	

F.3 REFERENCES

[F1] European Fifth Framework Program Contract no. FIKI-CT-2001-00169 "HTR-N1", signed 20. September 2001.

[F2] H.J. Ruetten, "HTR-N1 WP3.1: Plutonium (second generation) burnup benchmark (proposal)", private communication to HTR-N1 WP3 partners, 28. September 2001; discussed at HTR-N/N1 WP3 meeting of 28. May 2002.

[F3] J.C. Kuijper, Minutes of the WP3 meeting d.d. 28. May 2002, NRG note NRG/FAI/jkuijper/20206131, 14. June 2002, Attachment 12 to HTR-N/N1 5th Project Management Meeting information in SINTER.

[F4] J.C. Kuijper, H.J. Ruetten & B. Bonin, "Definition of reference coated particles and plutonium compositions (1st and 2nd generation Pu)", Document HTR-N-02/06-D-3.4.1 in SINTER, 25. June 2002; also see Appendix A.

[F6] J.C. Kuijper & J.B.M. de Haas, "Definition of common output parameters", Document HTR-N-01/02-D-3.1.5 in SINTER, 26. June 2002; also see Appendix D.

[F7] J.C. Kuijper, "Pu cell burnup benchmark", E-mail to HTR-N1 WP3 partners, 23. December 2002; see Section F.4, "Additional note".

F.4 ADDITIONAL NOTE

E-mail from J.C. Kuijper to HTR-N1 WP3 partners d.d. 23 december 2002:

```
At 23:40 23.12.02 +0100, j.c.kuijper@zonnet.nl wrote:

Note NRG/FAI/JCK/20212230

Dear HTR-N WP3 partners,

This message is a continuation of my previous message
concerning the "HTR-N1 Pu cell burnup benchmark (1st and
2nd generation Pu)".

After analysis of the Pu-II case (composition "C") it has
become clear that the moderator-to-fuel ration is too low
in the 3 g per pebble case, so that k-inf < 1.
A Pu-loading of 1.5 g Pu per pebble (and consequently a
total irradiation time of 1200 days at 1 kW per pebble)
at least gives k-inf > 1 for an appreciable part of the
total life time. The 1.5 g per pebble Pu-II case
(hence composition "C") will be inserted into the
benchmark specification. The 3 g Pu-II per pebble case
will also be retained as most (all?) partners will already
have calculated this case and the codes should show
good agreement for this case as well. A draft update
of the benchmark specifications will be inserted in SINTER
a.s.a.p. (after January 6, 2003).

Attached you will find k-inf versus burnup for 1 g
(1st generation Pu; composition "A" of the benchmark
specifications); 3 g (2nd generation Pu; composition
"C"_ and 1.5 g (2nd generation Pu; composition "C"),
as calculated by WIMS8A with a JEF-2.2 based 172-group
cross section library.

My apologies for any inconveniences caused, but I think
it is important also to have results which look more
or less realistic (fuel with k-inf < 1 is not regarded
as such). After all science is not the only thing we
have to worry about... (but I do hope it is still the
most important thing!!)

Kind regards and looking forward to a continued fruitful
collaboration in 2003 and beyond,

Jim Kuijper
WP3 manager

P.S. I will provide comments on any of the calculated
solutions already sent to me after January 6.
```


```
#
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#
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```