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APPLICATION OF SPECTRA ON PBMR V704 DESIGN

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ABSTRACT

The general purpose computer code SPECTRA has been used for thermal hydraulic simulations of the PBMR V704 design. SPECTRA was chosen as verification and validation (V&V) tool from a number of thermal hydraulic and accident analysis codes. The SPECTRA code is particularly suitable for HTR application because of its thermal radiation model, the reactor kinetics package, and the flexible way in which compressors and turbines can be modelled.

In the SPECTRA model of the PBMR V704 reactor vessel the full thermal radiation model was used, which calculates structure-to-fluid and structure-to-structure radiation based on gas emissivity/absorptivity, beam lengths and view factors. Thermal radiation from the pebbles to the graphite reflector and the vessel structures (and vice versa) was modelled.

The equation based approach of the SPECTRA pump/compressor model allows the user to define pump maps by specifying only a few typical parameters. The temperature and the gas velocity were included in the map definition of the turbines and compressors in the SPECTRA model of the PBMR V704. Surge degradation was included in the compressor maps.

The SPECTRA results have been compared to results calculated with FLOWNEX, a code specifically designed for PBMR. The results of the two codes were generally in good agreement. It was concluded that SPECTRA is a reliable tool for the independent V&V of the thermal hydraulic analyses of the PBMR facility, as required by the South African authority.

NOMENCLATURE

FLOWNEX	computer code used by PBMR
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HPTU	High Pressure Turbo Unit
HTR	High Temperature Reactor
ITM	Isotope Transformation Model
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LPTU	Low Pressure Turbo Unit
MELCOR	computer code developed by Sandia
PBMR	Pebble Bed Modular Reactor
PT	Power Turbine
RELAP	computer code developed by INEEL
rpm	revolutions per minute
SPECTRA	computer code developed by NRG
TRAC	computer code developed by INEL
V&V	Verification and Validation
Xe	Xenon

1 INTRODUCTION

A 400 MWth Pebble Bed Modular Reactor (PBMR) is currently under development in South Africa. The PBMR work being performed at present includes design and safety analyses. The start-up of the actual construction works will be launched shortly. The demonstration plant is expected to become operational in 2010.

Thermal-hydraulic analyses for the PBMR V704 design were performed by PBMR (Pty) Ltd using the FLOWNEX code. PBMR (Pty) Ltd contracted NRG for independent assessment (V&V, Verification and Validation) of the thermal-hydraulic analyses. The V&V project was completed in October 2004.

1.1 Plant description

The PBMR V704 is a helium cooled pebble bed reactor with a three-shaft power conversion unit based on a direct Brayton cycle (see Figure 1).

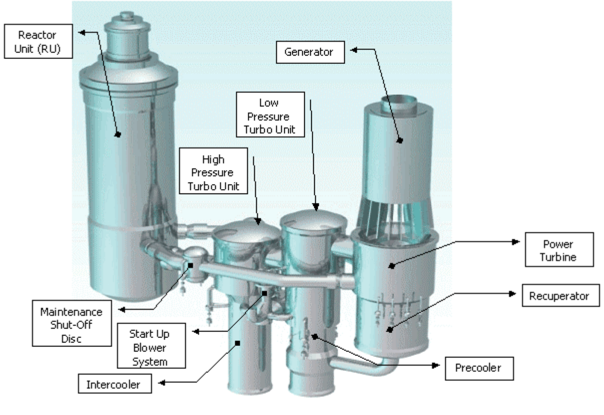


Figure 1 Overview of the PBMR V704 design.

The reactor vessel is a cylindrically shaped pressure vessel with a graphite column in the centre. The annulus around the central column is filled with fuel spheres with a diameter of 60 mm. In the thermal shield wall there are 36 inlet pipes in which the helium coolant flows upwards to the top of the core, from where it flows down through the core.

The High Pressure Turbo Unit (HPTU) consists of a turbine and a compressor on a single shaft. Similarly, the Low Pressure Turbo Unit (LPTU) features a turbine and compressor on one shaft. The helium coolant leaving the reactor vessel passes through the High Pressure Turbine (HPT) and the Low Pressure Turbine (LPT) before it reaches the Power Turbine (PT), the third shaft in this so-called 'three-shaft design'.

The Recuperator is a fin plate heat exchanger. It allows to improve the cycle efficiency by using the otherwise wasted heat of the gas discharged from the PT. Heat is transferred from the hot, low pressure helium coming from the PT to the cold, high pressure helium coming from the High Pressure Compressor (HPC).

Two finned-tube heat exchangers act as pre-cooler and inter-cooler. The helium is cooled by transferring heat to the cold water flowing inside the tubes.

The outlet of the HPC is connected to the manifold, which in turn is connected to the high pressure side of the Recuperator. After being heated in the Recuperator the helium is directed back to the Reactor Vessel via two inlet pipes.

Over the years several designs have been proposed and analysed. NRG has been involved in analyses for the design versions 5.01 [6], 5.02 [7] and 704 [8]. The present status is that the V704 design has been abandoned in favour of a single-shaft design. V&V of the new PBMR design with SPECTRA is expected to start in 2006.

1.2 Analysis tools selection

The capabilities of several thermal-hydraulic codes (TRAC-BF1/Mod1 [1], RELAP5/MOD3.2 [2], SPECTRA v2.00 [3], MELCOR v1.8.3 [4]) have been compared in order to determine the most suitable code for the specific characteristics of the PBMR system [5]. The initial selection of codes was based on their availability to NRG at the time, and the expertise of the NRG analysts. Based on this comparison, SPECTRA was proposed as the primary tool for the verification and validation of the PBMR thermal-hydraulic analyses. The main advantages of SPECTRA over the other codes are listed below. Note that some of the limitations of the codes may have been solved in later versions.

- Turbo-machinery modelling: SPECTRA offers a model similar to FLOWNEX, except that the maps are given by analytical functions with user-defined coefficients rather than tabulated data. RELAP offers a pump model, but the maps are cast in terms of volumetric flow rather than the "corrected flow" so they induce errors for speeds other than nominal. MELCOR contains a simple model "FANA" applicable only for nominal speed and a more general model "Quick-CF", where Control Functions are used to define the head. This model may theoretically be applied to model any turbomachinery, but it is quite tedious for data preparation, and quite difficult to run (stability of the CFs, which are explicitly coupled with the thermal-hydraulic solution).
- Multiple gases: The advantage of SPECTRA over RELAP, mentioned in [5], with respect to modelling multiple non-condensable gases is currently less an issue, since a multiple non-condensable gas option has been built into RELAP5/MOD3.3. Nevertheless the non-condensable gas option in RELAP remains a relatively unused, and weakly verified path. In TRAC some features exist to allow the presence of non-condensable gases in the system, but they have a very limited verification basis and can cause significant numerical problems when applied.
- The radioactive isotope transformation model, present in SPECTRA as part of the reactor kinetics package, allows to track decay chains of fission products. This allows to calculate for example Xe poisoning, release and transport of fission products. The model also supports fuel reloading, which can be used to simulate the adding/removing of fuel pebbles to/from the core. The other codes do not model core composition changes.
- Thermal radiation: SPECTRA contains a more general thermal radiation model. RELAP offers net enclosure with a non-absorbing/non-emitting gas. SPECTRA offers in addition a model with a participating gas.

The aforementioned models will be discussed in more detail in section 2.

2 SPECTRA MODELLING CAPABILITIES

2.1 General code characteristics

The SPECTRA code is an accident analysis code developed at NRG, the Netherlands. SPECTRA (Sophisticated Plant Evaluation Code for Thermal-hydraulic Response Assessment) is a computer program designed for thermal-hydraulic analyses of nuclear or conventional power plants. The models applied in the code were selected after an extensive literature review, as well as review of models available in other codes (CONTAIN, MAAP, MELCOR, RELAP, TRAC-BF1). The best available models were selected, which makes SPECTRA not only an accident analysis tool but also a library of physical models, well documented and tested, and easy to use [3].

The modelling approach is based on the Control Volume concept. A model of a certain physical system consists of Control Volumes (usually representing a physically bounded space, like a room, containment compartment, etc.), connected by Junctions. The approach is similar to that taken in for example CONTAIN or MELCOR.

The code contains a built-in library of fluid properties, consisting of the properties of water, steam, and several non-condensable gases. All gases are treated as real gases. The fluid properties are calculated using pre-computed tables, covering the range from 270 K to 3070 K, and from virtually 0.0 Pa to 1.5×10^7 Pa.

Besides the wide range of physical models and correlations that are available in SPECTRA, general-purpose utilities, called tabular and control functions, are also provided. With these functions the user can define certain quantities in the physics packages. They can be applied for example:

- to provide boundary conditions to the analysed problem,

- to model control systems of a reactor,
- to model safety system activations, etc.

More information about SPECTRA, including a description of all available models, can be found in [3]. In the next paragraphs three models are highlighted that are of particular interest to HTR modelling.

2.2 Neutronics

The Reactor Kinetics Package in SPECTRA consists of two models:

- Point Reactor Kinetics Model
- Isotope Transformation Model (ITM)

These models allow calculating the power behaviour of a nuclear reactor, including the immediate fission power and the power from decay of fission products. The effect of delayed neutrons is taken into account. Reactivity feedback from fuel temperature, moderator temperature and void fraction, as well as changes in core composition, are taken into account.

The core composition changes caused by fuel burn-up, production of poisons (such as Xe-135), and fuel reload, are calculated by the Isotope Transformation Model. The power resulting from the decay of fission products is also calculated by the ITM.

2.2.1 Reactor Kinetics Model: reactivity feedback test

SPECTRA analyses have been performed for the conceptual INCOGEN pebble bed reactor. These analyses included LOFA and LOCA scenarios in which reactivity feedback phenomena are important [9]. The reactivity effects calculated by SPECTRA have been compared to the results calculated by the 3D neutronics code OCTOPUS/PANTHERMIX [10][11]. Results from this comparison are shown in the figures below.

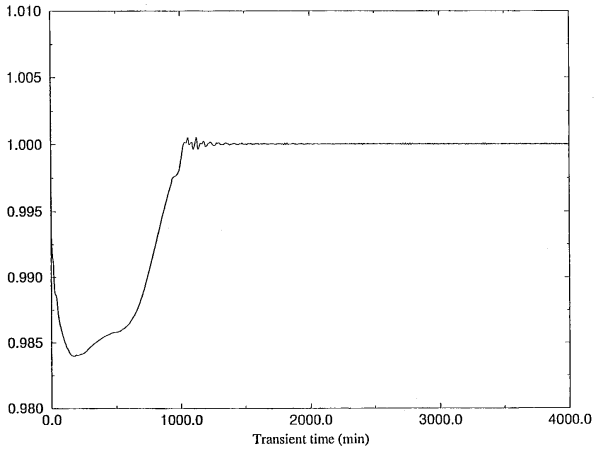


Figure 2 Total reactivity, INCOGEN, Loss Of Flow Accident; results of OCTOPUS/PANTHERMIX calculation.

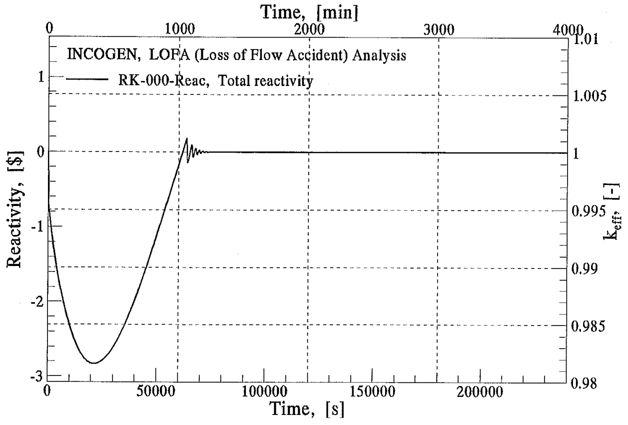


Figure 3 Total reactivity, INCOGEN, Loss Of Flow Accident; results of SPECTRA calculation.

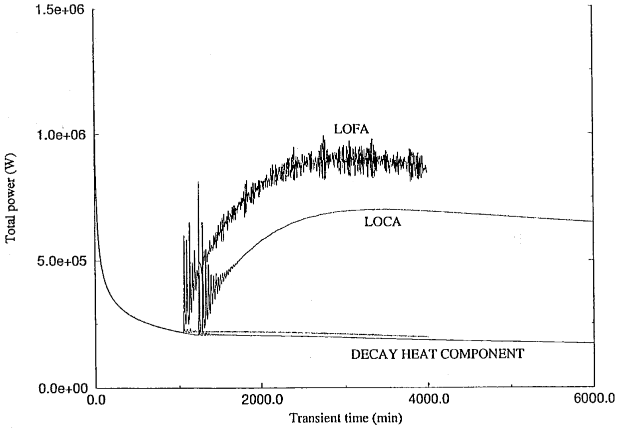


Figure 4 Reactor power, INCOGEN, cases: LOCA and LOFA, results of OCTOPUS/PANTHERMIX calculation.

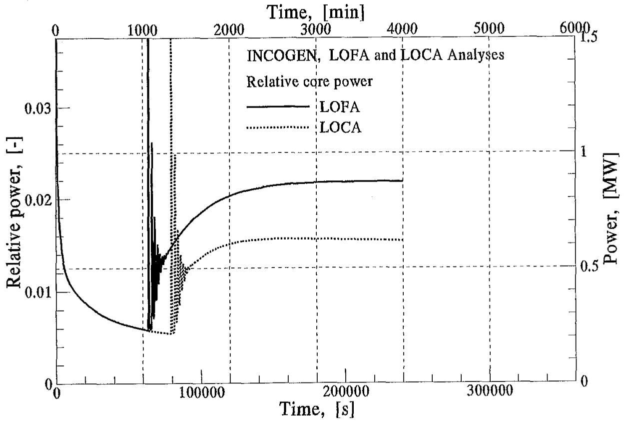


Figure 5 Reactor power, INCOGEN, cases: LOCA and LOFA, results of SPECTRA calculation.

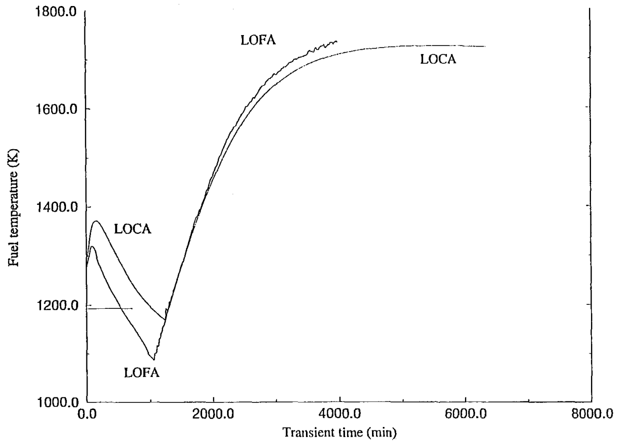


Figure 6 Fuel temperature, INCOGEN, cases: LOCA and LOFA, results of OCTOPUS/PANTHERMIX calculation.

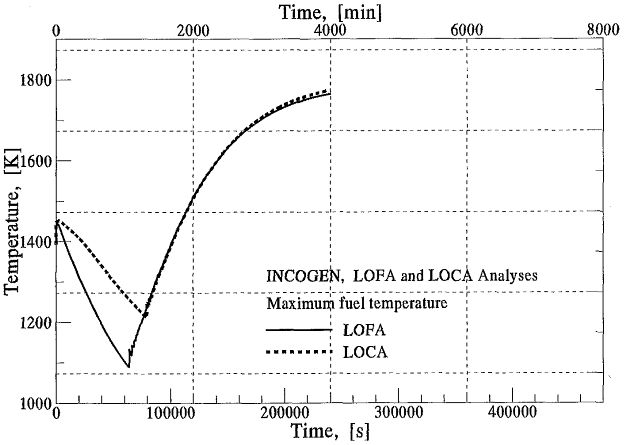


Figure 7 Fuel temperature, INCOGEN, cases: LOCA and LOFA, results of SPECTRA calculation.

Figure 2 through Figure 7 show that the point kinetics model in combination with the Isotope Transformation Model allows SPECTRA to calculate LOFA and LOCA scenarios for the pebble bed reactor type. The reactivity feedback from fuel temperature and xenon poisoning that was calculated by SPECTRA is in good agreement with results of the 3D neutronics code OCTOPUS/PANTHERMIX. It should be noted that the point kinetics model is only valid for homogeneous cores, i.e. reactors in which the pebbles are being recycled, such as the PBMR design.

2.2.2 *Isotope Transformation Model: calculation of pebble reloading*

To compensate for the changes during reactor operation, fuel pebbles with high burn-up must be replaced by fresh ones. In the SPECTRA model of PBMR V5.01 this is modelled by activating the built-in fuel reloading/removal option. A simple proportional control function was designed to calculate the refueling rate needed to keep a constant power:

$$R(t) = C(P - P_0)$$

where	$R(t)$	reloading rate [1/s]
	C	proportionality constant, [1/s/W]
	P_0	designated power, [W]
	P	power, [W]

The SPECTRA results [6] have been compared to calculations done with PANTHERMIX and VSOP [12]. The results are shown in Table 1. There is reasonably good agreement between the three codes.

Table 1 Fuel reload rate, steady-state calculations with reactor kinetics; SPECTRA, PANTHERMIX and VSOP models for PBMR V1.00.

Code	Reload rate [pebbles/day]
PANTHERMIX	343
VSOP	377
SPECTRA	420

2.3 Compressors and turbines

2.3.1 *Approach for pumps/compressors*

The basic approach in the SPECTRA code is quite different from codes such as RELAP, TRAC, etc. These codes require the user to provide data tables specifying maps for all possible conditions (four quadrant curves). Alternatively, they offer built-in curves for typical pumps (e.g. Bingham Westinghouse pump curves are available in RELAP).

In general, it is difficult to find sufficient data to determine the four quadrant curves; specifically data for reverse speed and reverse flow are typically not available from the manufacturer. The required input data is extensive; the user must provide a sufficient amount of data to cover all possible conditions, even if some conditions are never expected to occur. Consequently users of RELAP or TRAC typically prefer to use the built-in maps. Thus the modelling is either tedious or not flexible.

The pump/compressor model in SPECTRA was designed to provide flexible modelling, while simultaneously limiting the amount of effort required for input data preparation. The pump/compressor maps are approximated by a standard equation, which is built into the code. The coefficients in this equation are defined by the user. The user has therefore to define only a few input parameters that will define the entire pump/compressor map.

2.3.2 *Pump/compressor maps - ideal map with no surge*

The pump/compressor map is approximated in SPECTRA by the parabolic equation

$$\Delta P_R = C_P \omega^a \pm \left(C_P - 1\right) V_R^2 \ \omega^b \qquad \text{for } \omega > 0.0$$
$$\Delta P_R = C_{DR} C_P \ \omega^a \pm \left(C_P - 1\right) V_R^2 \ \omega^b \qquad \text{for } \omega < 0.0$$

where

ΔP_R Reduced pressure head, [-], equal to:

$$\Delta P_R = \frac{\Delta P(t)}{\Delta P_N}$$

where ΔP_N, is the nominal pressure head, [Pa]. There are two options in the code. The user can specify the nominal pressure head or the nominal pressure ratio, Π_N, [-]. In the first case ΔP_N is constant; in the second case it is equal to $\Delta P_N(t) = \Pi_N \cdot P_0(t)$, where $P_0(t)$ is the current pressure upstream the pump. The first option is appropriate for pumps; the second is appropriate for gas compressors.

V_R	Reduced flow, [-]
ω_R	Reduced speed, [-]
C_P	Constant defining the shape of pressure head in pump map, [-], CP > 1.0.
C_{DR}	Degradation factor for negative (reverse) speed, [-], $-1.0 < C_{DR} < 1.0$.
a	First exponent (default value of 2.0).
b	Second exponent (default value of 1.0).

In the above equation the sign is – in case of positive flow, and + in case of negative flow. The parameters C_P, C_{DR}, *a*, and *b* are user-defined. Together these four parameters enable the user to change every aspect of the shape of the curve, thus allowing him to closely approximate any pump map. The influence of the parameters on the shape of the map can be seen in Figure 8. More discussion on these parameters can be found in [3].

2.3.3 *Degradation of compressor head in low flow range (surge model)*

In the low flow range, machines such as the PBMR V704 compressors (HPC and LPC) typically lose their capability to provide head. This is called "surge". In SPECTRA two input parameters are available to model the pump/compressor behaviour in the low flow range. These are:

C_{VS}	relative volumetric flow at which degradation begins, defined as a ratio of the flow at which surge starts to the flow at zero pressure head at nominal speed (see Figure 8),
C_{DS}	degradation factor, defined as the ratio of the degraded pressure head at zero flow to the un-degraded pressure head at zero flow (resulting from the un-degraded pump/compressor model equation - see Figure 8).

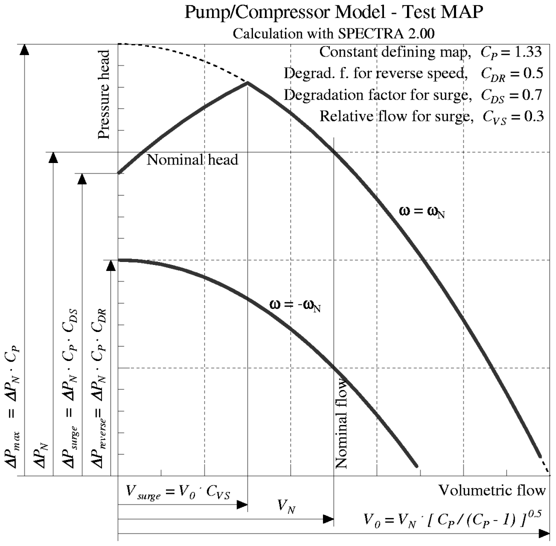


Figure 8 Influence of input parameters C_P, C_{DR}, C_{DS}, and C_{VS} on the pump map.

2.3.4 *SPECTRA model of PBMR V704 compressors*

The compressor maps for the HPC and LPC were provided by the manufacturer. The input parameters that give the best approximation of the maps have to be found by trial & error. The values that were used for the HPC are shown in Table 2 and Table 3. The resulting compressor map, as calculated by SPECTRA, is shown in Figure 9. It is seen that by specifying only 5 parameters, good agreement for a pump/compressor curve can be obtained with the approach implemented in SPECTRA.

Table 2 Input parameters for SPECTRA model of HPC.

Parameter	Value
Pump/compressor map constant, C_p [-]	3.1
Compressor map exponent, *a* [-]	2.9
Compressor map exponent, *b* [-]	0.7

Table 3 Surge definition for SPECTRA model of HPC ($\omega_N = 100\ s^{-1}$)

Surge degradation factor, C_{DS} [-]	0.01	
Relative volumetric flow, C_{VS} [-] = $f(\omega)$	ω [s^{-1}]	C_{VS} [-]
	50.0	0.72
	70.0	0.74
	90.0	0.76
	100.0	0.78
	110.0	0.80
	120.0	0.82
	130.0	0.84

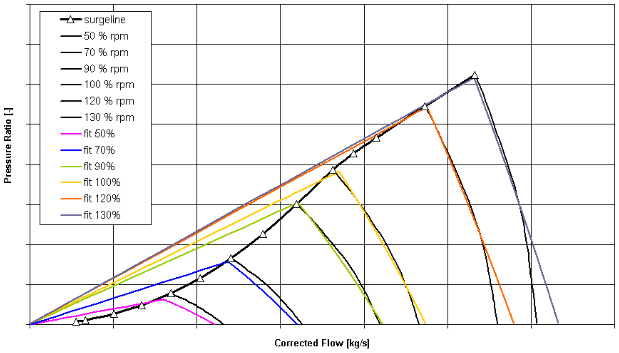
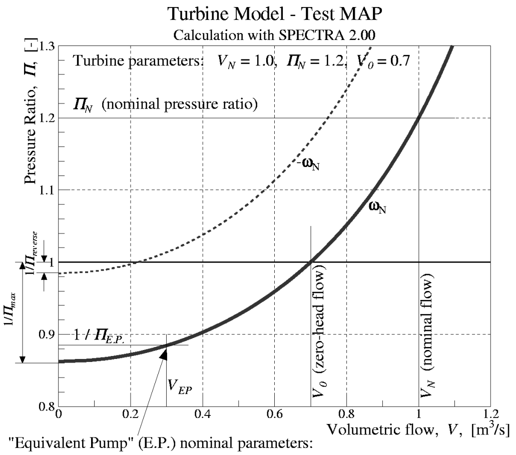


Figure 9 HPC map; source data (black lines) and SPECTRA model with $C_p = 3.1$, $a = 2.9$ and $b = 0.7$. Note: The method that was used to generate this graph does not yield any plot points for the conditions in which surge occurs. The figure therefore shows straight lines from the surge line to the origin, whereas in reality these lines are curved.

2.3.5 *Approach for turbines*

The turbine model in SPECTRA is based on the same approach as the pump/compressor model (see 2.3.2). The turbine nominal parameters, such as nominal flow and pressure ratio or head, are internally converted by the code into nominal parameters of an "equivalent pump", as shown in Figure 10. The equivalent pump is defined as a pump/compressor that has exactly the same map as the turbine, if the map is plotted in terms of the pump pressure ratio (outlet divided by inlet pressure) rather than the turbine pressure ratio (inlet divided by outlet pressure).

The "equivalent pump" approach allows to perform turbine calculations using the same subroutines that calculate pumps/compressors. The equation defining turbine behaviour is therefore exactly the same as the equation defining pump/compressor map, and is therefore not discussed here.



"Equivalent Pump" (E.P.) nominal parameters:

$V_{E.P.} = V_0 [(C_P - 1) / C_P]^{0.5}$

$\Pi_{E.P.} = 1 + (1 - 1/\Pi_N) / [(C_P - 1) (V_N / V_{E.P.})^2 - C_P]$

Figure 10 Turbine map - conversion of the turbine parameters into "Equivalent Pump" parameters, performed internally by the code.

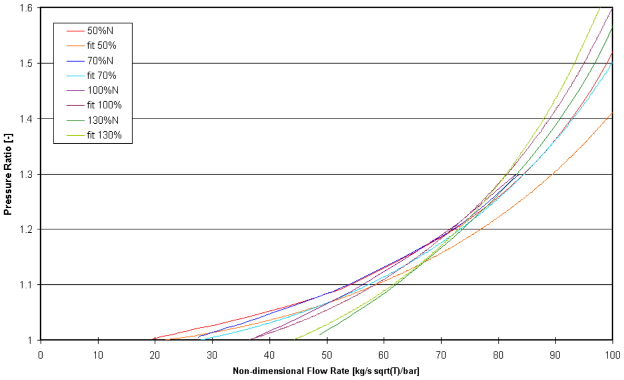


Figure 11 HPT map; source data and SPECTRA model with $V_0 = 26.0$, a = 2.0 and b = 0.5.

2.3.6 *Turbine-compressor coupling*

The SPECTRA code provides two options to determine the speed of a turbine, compressor or pump. First, the speed can be determined by a user-defined tabular or control function, in other words the speed may be an arbitrary function of time: $\omega = f(t)$. The second option is to use the rotor inertia equation.

Since the turbine and the compressor are on the same shaft, they both have the same speed and there is only one inertia equation specifying the speed of both machines. Bearing in mind the two options available in SPECTRA to determine the speed, this can be achieved in three ways:

- The inertia equation may be used to calculate the turbine speed, and the compressor speed may be set to be equal to the turbine speed.
- The inertia equation may be used to calculate the compressor speed, and the turbine speed may be set to be equal to the compressor speed.
- The inertia equation may be used for both machines.

In the first and the second method, a control function is used to take the calculated speed from one unit and use it as input for the other unit. The three methods mentioned above were applied in test runs. It was observed that the first two methods provide the same results, i.e. it is not important which machine is using the inertia equation. The differences in transient speed calculated with these methods were within 1%. The third method turned out to be inappropriate. Since both machines were using independent equations, their speeds, although similar, were somewhat different because of inevitable differences during iterations to provide an implicit solution. These small differences accumulated over time and during a long transient there was a visible difference between the turbine and the compressor speed.

Based on these observations it was decided to use the first method on the above list, in other words to use the rotor inertia equation for the turbine. The equation is:

$$I\frac{d\omega}{dt} = T_m - T_{hydr} - T_{fric}$$

where ω is the turbine speed, T is torque, and the subscripts *m, hydr* and *fric* signify the machine receiving power, hydraulic and friction torque respectively. The friction torque is assumed to be proportional to the speed, with the proportionality constant C_f, ($T_{fric} = C_f |\omega|$).

The turbine power, Q_{hydr}, is calculated by SPECTRA using the isentropic efficiency entered by the user. The power is given by:

$$Q_{hydr} = \eta\, V \rho\, c_P\, T\, \left((1/\Pi)^{(\kappa-1)/\kappa} - 1 \right)$$

where Π is the pressure ratio, and η is the isentropic efficiency. The power is normally negative, i.e. the power is taken from the fluid. If the power changes sign to positive (the power is given to the fluid), then η is replaced by $(1/\eta)$. The efficiency of the turbines at different speeds was provided by the manufacturer, and is defined in SPECTRA separately for the positive and the negative flow.

2.4 Thermal radiation

The Thermal Radiation Model, available in SPECTRA, is based on net enclosure with grey surfaces and non-grey gas (Hottel gas) approximations. Two radiation models are available:

1. Radiation in an enclosure with a non-absorbing/non-emitting medium
2. Radiation in an enclosure with a participating gas.

A radiating system (a part of the model for which the thermal radiation model is activated) is characterized by a consistent set of view factors and, if the second model is used, by a set of mean beam lengths between surfaces. When all radiating surfaces of the given system are selected, a matrix defining view factors (also known as shape factors) must be supplied.

The view factors must fulfill the reciprocity relation, and the enclosure relation. The reciprocity relation is ([13]):

$$A_i F_{ij} = A_j F_{ji}$$

where
A_i area of radiating surface i, [m^2]
F_{ij} view factor from surface i to surface j, [-]

The enclosure relation is ([13]):

$$\sum_{j=1}^{N} F_{ij} = 1.0$$

where N is the total number of radiating surfaces. The enclosure relation expresses the fact that within a given radiating system all radiant energy leaving surface i must be intercepted by some surface of the enclosure (including i itself if it is concave). If the enclosure relation is not fulfilled, then a system will not be conserving energy.

2.4.1 Assumptions of the Thermal Radiation Model

The theoretical basis of the Thermal Radiation Model is described in more detail in references [14] and [15]. Model 1, without participating gas, is based on the following assumptions:

1. The enclosure can be divided into a finite number of isothermal surfaces.
2. Surfaces are gray body emitters, absorbers and reflectors.
3. Direction distribution of radiation leaving the surface obeys Lambert's Cosine Law.
4. Radiant energy leaving any surface is uniform over that surface.

At each surface of the enclosure an equation can be written expressing the fact that the flux of radiant energy leaving the surface is the sum of the emitted radiation plus the reflected radiation (see [15], section 2.1):

$$A_i H_i = A_i \varepsilon_i E_i + \rho_i A_i G_i$$

where

A_i	area of the surface i, [m2]
H_i	radiosity, radiant energy leaving surface i per unit area, [W/m^2]
E_i	ith surface black body emission power, equal to: σT_i^4, [W/m^2]
G_i	radiation coming from other surfaces to surface i, per unit area of the surface i, [W/m^2]
ε_i	emissivity of the surface i, [-]
ρ_i	reflectivity of the surface i, [-]

The radiation coming at the surface i is equal to:

$$A_i G_i = \sum_{j=1}^{N} A_j H_j F_{ji}$$

where

F_{ij}	*view factor from the surface i to the surface j, [-]*
N	*number of radiating surfaces*

Thus the basic equation has the form:

$$A_i H_i = A_i \varepsilon_i E_i + \rho_i \sum_{j=1}^{N} A_j H_j F_{ji}$$

The surface blackbody emission power, E_i, is, according to Stefan-Boltzmann's law, equal to: $E_i = \sigma T_i^4$, where: σ is the Stefan-Boltzmann's constant, [W/m^2/K^4], (equal to 5.670×10^{-8} [16]), and T_i is the temperature of the surface i, [K].

Surface reflectivities of the gray surfaces, ρ_i, are equal to: $\rho_i = 1 - \varepsilon_i$. Taking into account the relation between ε_i and ρ_i, and the reciprocity law: $A_i \times F_{ij} = A_j \times F_{ji}$, the above equation may be written as:

$$H_i = \varepsilon_i E_i + (1 - \varepsilon_i) \sum_{j=1}^{N} H_j F_{ij}$$

The above equation, written for each of the N radiating surfaces, defines a set of N linear equations with respect to H_j.

When all radiosities, H_i, are determined, the heat flux lost from the surface i due to thermal radiation, can be calculated as a difference between the radiosity and the incoming radiation flux ([15], section 2.1):

$$A_i q_i = A_i H_i - A_i G_i$$

or:

$$q_i = H_i - \sum_{j=1}^{N} H_j F_{ij}$$

where q_i is the heat flux lost from the surface i due to thermal radiation, [W/m^2]. It is interesting to note that the sum of radiation heat fluxes from all surfaces is equal to:

$$\sum_{i=1}^{N} A_i q_i = \sum_{i=1}^{N} A_i H_i - \sum_{i=1}^{N} \sum_{j=1}^{N} A_i H_j F_{ij}$$

Using the reciprocity relation the above equation can be rewritten as:

$$\sum_{i=1}^{N} A_i q_i = \sum_{i=1}^{N} A_i H_i - \sum_{i=1}^{N} \sum_{j=1}^{N} A_j H_j F_{ji} = \sum_{i=1}^{N} A_i H_i - \sum_{j=1}^{N} A_j H_j \sum_{i=1}^{N} F_{ji}$$

From the closure relation it follows that $\Sigma F_{ji} = 1.0$, and finally:

$$\sum_{i=1}^{N} A_i q_i = \sum_{i=1}^{N} A_i H_i - \sum_{j=1}^{N} A_j H_j = 0.0$$

Thus the total radiative energy is conserved, provided that the reciprocity and closure relations are fulfilled.

2.4.2 SPECTRA core model

In HTR reactors, where coolant temperatures are typically around 800 to 900 ºC, thermal radiation provides an important contribution to the overall heat transfer and should be included in the model in order to correctly calculate the temperatures of the coolant and the core structures. Unlike many other codes SPECTRA does not use an effective conductivity correlation, but a mechanistic approach including radiation, convection and conduction. A special program was developed to determine the pebble bed view factors.

The SPECTRA results for the steady-state analysis of the V5.01 design have been compared with values from the PBMR Safety Analysis Report (2000), and the data were found to be in good agreement with each other [6]. Figure 12 shows the gas temperatures at different positions in the core.

It is seen that the temperature profiles in both axial (height) and radial direction (active outer region vs. inactive central region) correspond well to the reference data.

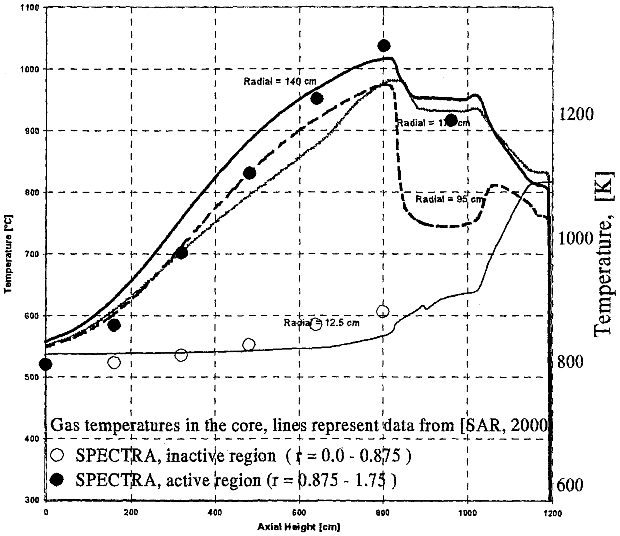


Figure 12 Gas temperatures in the core, comparison of SPECTRA with data from PBMR Safety Analysis Report.

3 V&V OF PBMR V704

The Verification and Validation of the PBMR V704 design consisted of two steps:

- Step 1: Separate component modelling and testing.
- Step 2: Integrated system modelling and testing.

In the first step models of separate components (i.e. reactor vessel, heat exchangers, etc.) were built and tested. In the second step the separate components were integrated into a full system model.

To ensure independence of the current verification procedure the calculations were performed “blind”. This means that the SPECTRA model was built and the calculations were performed without knowing the FLOWNEX model, or the FLOWNEX results. Some results from the calculations are discussed below.

Table 4 shows the steady-state results of the HPTU. The observed differences in the main parameters such as speed, efficiency, power, pressure ratio, inlet and outlet temperatures and pressures, and mass flows are all within 3%. The only exception is the surge margin which is not calculated by SPECTRA and had to be interpolated from the compressor map, a method that can result in large deviations even if the maps are only slightly different.

Table 4 Steady-state HPTU calculation results, SPECTRA and FLOWNEX model of PBMR V704.

Parameter	FLOWNEX	SPECTRA	Diff.	[%]
Rotational speed [RPM]	6060	6060	0	0.0
HPC surge margin [%]	13.0	7.7	-5.3	-41
HPC fluidic Power [MW]	75.85	77.20	1.35	1.8
HPC efficiency [%]	90.8	90.6	-0.2	-0.2
HPC pressure ratio [ ]	1.6806	1.6895	0.0089	0.5
HPT fluidic power [MW]	76.62	77.20	0.58	0.8
HPT efficiency [%]	88.4	88.3	-0.1	-0.1
HPT pressure ratio [-]	1.2219	1.2222	0.0003	0.0

The results of the transient calculation showed a discrepancy in the response time of the turbo machinery, but this was later discovered to be a bug in the SPECTRA code that was easily corrected. A difference in the HPC efficiency during the transient was also observed. This is most likely caused by different interpolation methods that were used by the codes to calculate the efficiency at a certain speed from the efficiency tables provided by the manufacturer. Figure 13 illustrates why linear interpolation does not always work properly for this kind of data: the weighted average between the values at 58.3 rpm (red line) and 81.7 rpm (blue line) would give an efficiency of (0.0+0.92)/2 = 0.46, whereas the correct value at this speed (70 rpm, cyan line) is about 0.78.

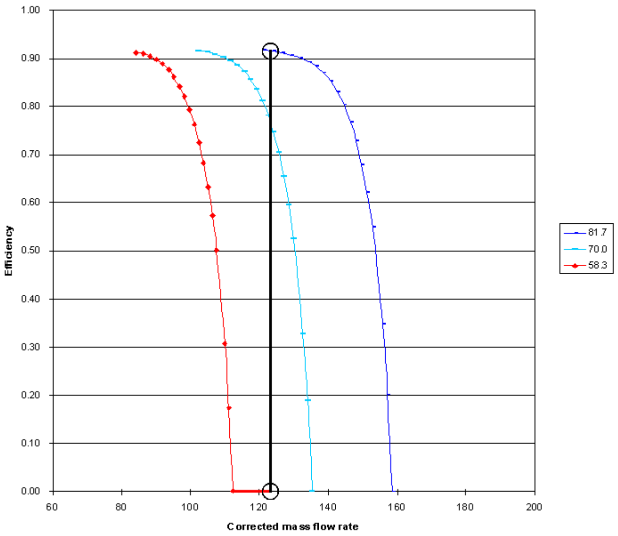


Figure 13 Linear interpolation of efficiency curves for different speeds can give wrong answers.

The comparison between SPECTRA and FLOWNEX for all seperate component models as well as the integrated model is described in [17]. The results of the two codes were generally in good agreement.

4 CONCLUSION

The general purpose computer code SPECTRA has been used for thermal hydraulic simulations of the PBMR V704 design. SPECTRA is particularly suitable for HTR application because of its reactor kinetics package, the compressor/turbine model, and the thermal radiation model. Comparison to other codes (3D, neutronics) shows the good performance of the reactor kinetics model and the thermal radiation model.

Results of the steady-state and transient analyses performed with SPECTRA and FLOWNEX also show good agreement. The observed differences in the main system parameters such as power, temperatures, pressures, and mass flows are within a few percent.

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