A Three Dimensional Two Energy Group Coupled Reactor Physics and Thermal Hydraulics Code (M32) – A Tool for Student Design Studies

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This paper describes a new code M32 that has been developed to perform coupled reactor physics and thermal hydraulic calculations undertaken in student reactor design studies. M32 is a general three-dimensional, two-energy group code that couples a diffusion theory representation of the core with a thermal hydraulic description that accounts for the heat flux and coolant enthalpy rise. A sample application examining the feasibility of a high temperature helium cooled reactor based on the General Atomics GT-MHR design for marine applications is described. M32 has been demonstrated to be a useful addition to the portfolio of computational tools for education and training in reactor design methodologies.

KEYWORDS: reactor physics, thermal hydraulics, high temperature gas cooled, education

1. Introduction

As part of providing postgraduate students with the education and training in nuclear reactor design methodologies various computational techniques can be used, ranging from simple spreadsheet based work packages to industry standard codes. The use of such tools in a portfolio of computer assisted learning packages was described at PHYSOR 2002 [1]. However, in general there has been a lack of a basic coupled code that fills the gap between simple spreadsheets and industry standard codes. In this paper we describe the PC based M32 code [2] that is intended to address this gap and so provide a simple scoping tool for student reactor design studies. To demonstrate the application of M32 in a study investigating the feasibility of a high temperature gas cooled reactor for marine propulsion applications is described.

The Gas Turbine Modular Helium Reactor (GT-MHR) currently underdevelopment in a joint venture between General Atomics and Minatom [3] was selected as the reference design for this work. The GT-MHR is a 600 MW_{th} helium cooled, graphite moderated system utilizing TRISO type fuel particles contained within fuel compacts that are themselves then arranged within hexagonal graphite fuel modules. The hexagonal fuel modules are arranged in an annular fashion with both an internal and external graphite reflector. The key parameters of the GT-MHR are summarized in Table 1.

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Table 1 Reference GT-MHR Design Parameters

Parameter	*GT-MHR*
Core Configuration	Prismatic block, with the fuelled region in an annulus
Moderator	Graphite (internal and external)
Coolant	Helium
Fuel	TRISO fuel particles with 19.9 % enriched ^{235}U
Control Rods	Boron Carbide
Power Density	6.6 MW m^{-3}
Average Coolant Temperature	692 °C
Mass Flow Rate	320 kg s^{-1}
Pressure	7 MPa
Thermal Power	600 MW
Power Conversion	Direct Brayton Cycle with intercoolers
Plant Efficiency	≈ 48 %

2. Description of M32 – A Tool for Student Design Studies

M32 is a three-dimensional, two-energy group code that couples a diffusion theory representation of the core with a thermal hydraulic description that accounts for the heat flux and coolant enthalpy rise. M32 uses an x-y-z coordinate system, Figure 1, to represent the core volume; the origin is located at the centre of the core face (x, y) and at the bottom of the core (z = 0). Therefore the model will be a quarter core representation. Each coordinate axis is uniformly divided in units of Δx, Δy and Δz such that volume elements ΔV, referred to as a cells, are formed. A stack of such cells over the entire height of the core is referred to as a 'stick'. M32 is currently limited to a maximum of 10 (x) by 10 (y) by 20 (z) cells. Individual cells are addressed by three co-ordinates *i, j* and *k*. The *k* index is the axial slice number. The *i* and *j* index the cells in the x and y direction respectively. Nuclear and thermal data is allocated to each cell by specifying the total number of cells associated with this data set, starting at the origin. Therefore, as the core properties are built up, an overlay of data occurs whereby the most recently specified data are taken as the final properties of that cell.

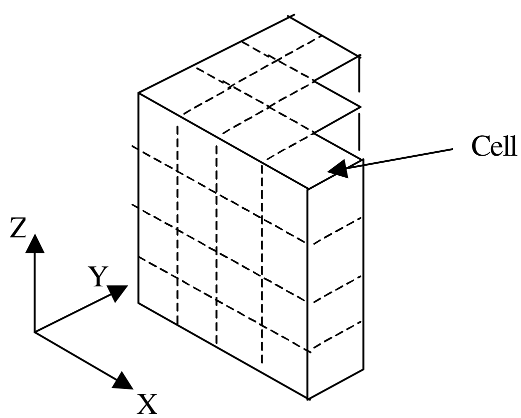

Figure 1 M32 Core model geometry

With respect to nuclear data M32 requires that the macroscopic absorption, fission and intra-group scatter cross-sections together with the diffusion coefficient for both groups are supplied in ASCII format input file for each cell or stick. In this study the well know *SERCO Assurance* [4] deterministic reactor physics code package WIMS 8A was used to prepare these two-group energy condensed and spatially homogenized constants, discussed in Section 3.1.

The diffusion theory describing equations used in M32 are given below in Equations 1 (fast) and 2 (thermal).

$$\frac{1}{\upsilon_1}\frac{d\phi_1}{dt} = \frac{d}{dx}\left(D_{x1}\frac{d\phi_1}{dx}\right) + \frac{d}{dy}\left(D_{y1}\frac{d\phi_1}{dy}\right) + \frac{d}{dz}\left(D_{z1}\frac{d\phi_1}{dz}\right) - \left(\Sigma_{a1}+\Sigma_{s1}\right)\phi_1 + \Sigma_{s2}\phi_2 + \frac{\nu}{k}\left(1-\beta\right)\left(\Sigma_{f1}\phi_1+\Sigma_{f2}\phi_2\right) + \sum_{i=1}^{6}\lambda_i C_i + S_1 \quad (1)$$

$$\frac{1}{\upsilon_2}\frac{d\phi_2}{dt} = \frac{d}{dx}\left(D_{x2}\frac{d\phi_2}{dx}\right) + \frac{d}{dy}\left(D_{y2}\frac{d\phi_2}{dy}\right) + \frac{d}{dz}\left(D_{z2}\frac{d\phi_2}{dz}\right) - \left(\Sigma_{a2}+\Sigma_{s2}\right)\phi_2 + \Sigma_{s1}\phi_1 + S_2 \quad (2)$$

where,

Σ_{a1},Σ_{a2}	Fast and thermal macroscopic absorption cross-section
Σ_{f1},Σ_{f2}	Fast and thermal macroscopic fission cross-section
Σ_{s1},Σ_{s2}	Fast and thermal macroscopic intra-group cross-section
D_x, D_y, D_z	Fast and thermal diffusion coeff. in x,y and z direction
β	Delayed neutron fraction
λ_i	Decay constant of i^{th} delayed neutron precursor group
C_i	Precursor concentration of i^{th} group
S_1, S_2	Neutron source (if present)

Within M32 three principle thermal feedback mechanisms can be modeled. The effect of the variation in coolant temperature and consequently density is modeled by considering both the variation in the fast to thermal group scattering and the thermal group absorption. However, in this study the effect of variation in the helium coolant gas temperature was ignored as it was considered that the helium had no significant neutronic effects. The effect of fuel temperature variation is modeled by considering its effect on the fast group absorption using the relationship given in Equation 3. The value of c_3 must be supplied by the user in the input file.

$$\Sigma_{a1}(T) = \Sigma_{a1}(0)\left[1 - c_3\left(1 - \frac{T}{T_0}\right)\right] \quad (3)$$

where,

$\Sigma_{a1}(T)$	Fast macroscopic absorption cross-section at fuel temperature T
$\Sigma_{a1}(0)$	Fast macroscopic absorption cross-section at nominal fuel temperature
T_0	Nominal fuel temperature

With respect to thermal hydraulics in M32 it is assumed that heat flow is normal to the heat transfer surface and consequently that the temperature distribution moving in the direction of coolant flow in a stick is described by Equation 4. Heat generation is assumed to only occur in the fuelled region (zero elsewhere) and represents both fission power and decay heat and is described by Equation 5, the user must supply the value of d at run-time. The time dependence of decay heat post shutdown is represented within M32 by Equation 6. Whilst, a relatively simplistic representation of this phenomenon it is considered adequate for times up to 1000 seconds after shutdown.

$$\left(\rho c_p \Delta z\right)\frac{dT(r,t)}{dt} = \frac{d}{dr}\left(\kappa p \Delta z \frac{dT(r,t)}{dt}\right)\Delta r + A\Delta z q(r,t) \qquad (4)$$

where,

r	Linear measure in the direction of flow i.e z coordinate
ρc_p	Heat capacity
$A\Delta z$	Volume of stick under consideration
κ	Thermal conductivity
$p\Delta z$	Heat transfer area
$q(r,t)$	Heat genertion

$$q(r,t) = 3.2041\times10^{-14}.\frac{Vd}{V_{fuel}}.\left(\left(\Sigma_{f1}\phi_1 + \Sigma_{f2}\phi_2\right)_t + \frac{Fd}{(1-d)}\left(\Sigma_{f1}\phi_1 + \Sigma_{f2}\phi_2\right)_0\right) \qquad (5)$$

where,

d	Decay heat as a fraction of intial power
0 suffix	Intial conditions
t suffix	Conditions at time t
F	Time dependence of decay heat

$$\begin{aligned} &F = 1 \quad \text{For all } t \text{ pre shutdown} \\ &F = (1 - 0.096\ln\left[1 + (t - t_{shutdown})\right]) \text{ for all } t \text{ post shutdown} \end{aligned} \qquad (6)$$

The governing differential equations, Equations 1,2 and 4 are represented in M32 in a form suitable for numerical analysis through the use of finite difference methods. In M32 a backward implicit method rather than the more traditional central difference method has been adopted as it offers enhanced numeric stability, however, it is more sensitive to the time step size. This effect is demonstrated in the analysis of time step sensitivity reported in Section 3.3.

3. A sample application of M32 – "A feasibility study of a High Temperature Gas Cooled Reactor for Marine Applications"

The scope of this feasibility study was limited to the following aspects; the reactor physics design of the core and the thermal hydraulic behavior of the system. To estimate the required thermal power the predicted typical hotel and propulsion electrical loads were assumed. This study concluded that a thermal power of 67 MW would be required.

A number of design constraints were imposed most significantly that 'standard' GT-MHR modules should be utilized and that the power density should not exceed 6.6 MW m^{-3}. Consequently, the required core volume of 10.2 m^{-3} was calculated by scaling from the reference 600 MW_{th} design. The proposed core consisted of 37 800 mm high fuel modules arranged in three layers; a plan elevation of the proposed core is shown in Figure 2. Located above and below the fuelled region were 400 mm thick graphite top and bottom reflectors.

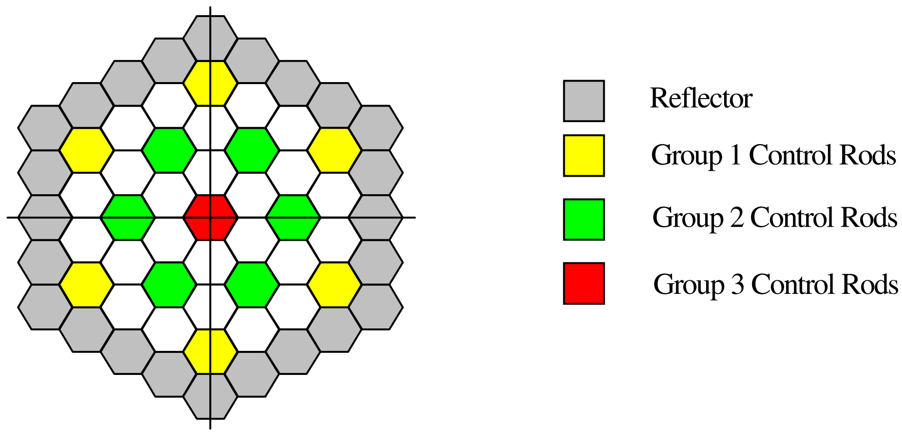

Figure 2 Plan elevation of proposed core

The reference GT-MHR design proposed boron carbide control rods, this scheme was also adopted for this study, however, to enhance the rod worth's the boron was assumed to be enriched to 95 % by atom ^{10}B. A symmetric rod scheme was examined that required 13 potentially rodded modules, shown in red, green and yellow in Figure 2.

3.1 Preparation of Two-group constants for use in M32

Deterministic neutronic calculations were conducted using the WIMS 8A code, all necessary nuclear data was taken from the standard 172-group WIMS JEF 2.2 data library [5]. A calculational route was developed that used the modules WHEAD/WMIX to generate the required macroscopic material cross-sections using the equivalence treatment in the resonance region. However, due to the double heterogeneity of the GT-MHR type fuel modules i.e. firstly the individual TRISO fuel particles within the fuel compacts and secondly the fuel compacts within each fuel module this treatment is inadequate. To account for the first level of heterogeneity the modules WPRES/WPROC/WRES were implemented. The module WPROC was specifically designed to determine collision probabilities for a system consisting of fuel particles embedded in a matrix and as such is ideally suited to TRISO type fuels. Subsequently the modules WSMEAR and WMERGE were used to generate an equivalent spatially homogenized material to represent the TRISO particles and the graphite matrix of the fuel compacts.

A detailed model, using the VVER geometry option, was then developed in the highly versatile characteristics method solver WCACTUS. Four module types were developed; a fully fuelled module with no control rod channel (Figure 3); a rodded fuel module with a boron carbide control rod (Figure 4); an unrodded fuel module with a helium filled control rod channel and an all graphite reflector module.

The modules WSMEAR and WCOND were then used to produce a single spatially homogenized material representative of the entire fuel module and to condense from the 172 library groups to a two-group model, with an energy boundary of 4 eV. Finally, modules WEDIT and WINTER were used to extract the required nuclear data constant.

Initially all materials in the model were considered to be at the nominal operating temperature of 692 °C and a set of nuclear data generated for all four module types. Subsequently, material temperatures in the range 500 °C to 1300 °C were assumed to investigate the resulting variation in the fast group absorption cross-section. A curve of the form given in Equation 3 was fitted to this data to determine the constant c_3 required by M32 to account for fuel temperature variation.

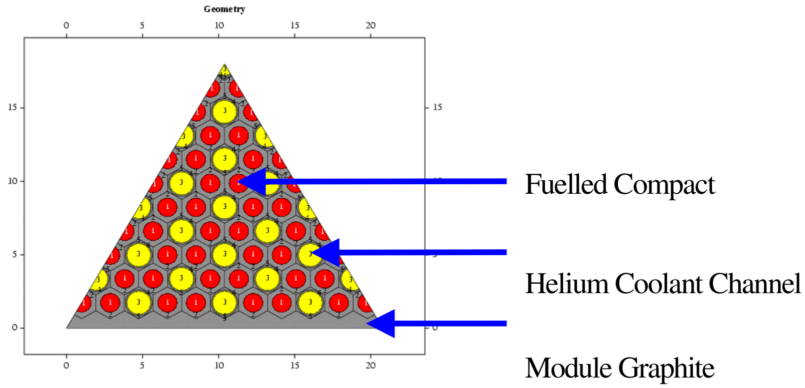

Figure 3 WCACTUS model of a fully fuelled module

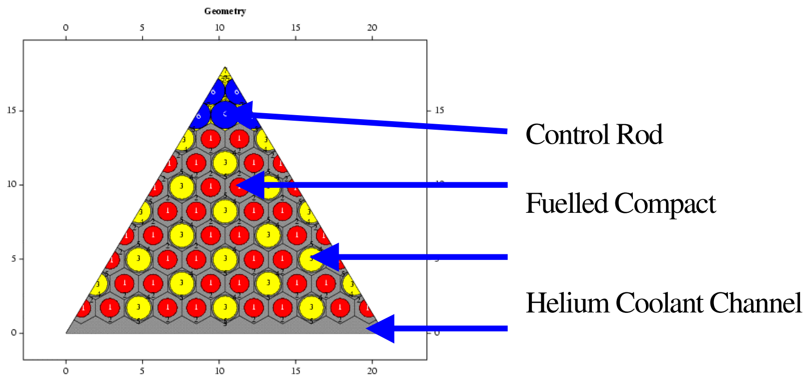

Figure 4 WCACTUS model of a rodded module

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3.2 Steady State study using M32

An input file for M32 was constructed that specified the core geometry, nuclear properties and thermal hydraulic characteristics. As previously discussed M32 represents the core using quarter core symmetry and a x-y-z coordinate system, therefore, an equivalent rectangular lattice conserving surface area was used to represent the hexagonal modules of the GT-MHR design, each hexagonal fuel module was represented by four sticks, shown in Figure 5. The core was represented by 16 axial slices each 200 mm thick and an 8 (209 mm) 8 (209 mm) x-y mesh, a x-y slice is shown in Figure 5.

The estimated critical banked rod position (ECP), rodded and unrodded start of life k_{eff} for this configuration as estimated by M32 are reported in Table 2. To investigate the effect of boron burnable poison addition two further nuclear data sets were generated with 0.5 % and 1.0 % by weight boron homogeneously distributed in the fuel compact matrix. The ECP, rodded and unrodded start of life k_{eff} for these cases are also shown in Table 2.

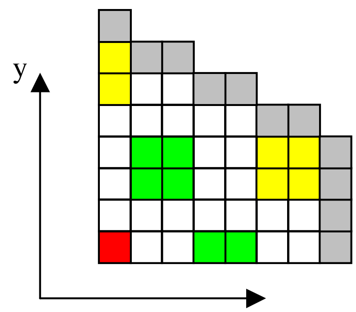

Figure 5 Slice through M32 representation of core

Table 2 Start of life parameters of proposed core

	Estimated Critical Position	Rodded Start of life k_{eff}	Unrodded Start of life k_{eff}
No boron	26 %	0.89	1.33
0.5 % by weight	39 %	0.82	1.16
1.0 % by weight	> 100 %	0.75	0.98

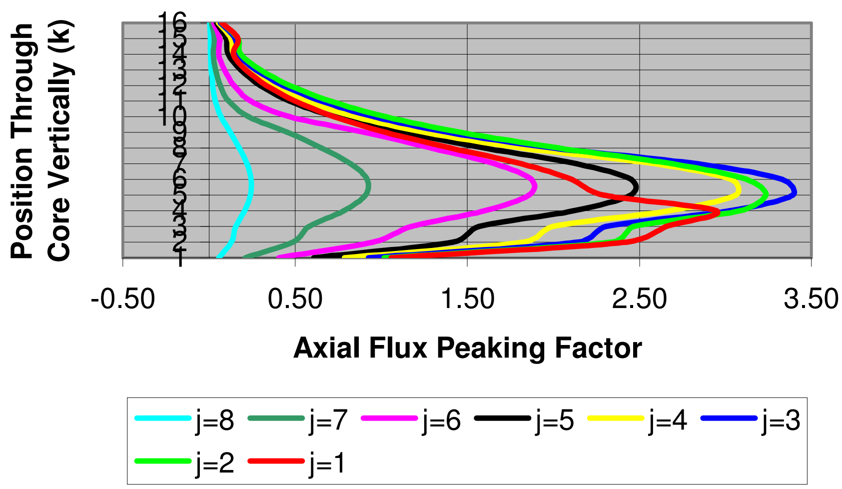

Figure 6 Axial flux peaking factor for column *i* =1

Together with banked operation, where all controls are at the same height, a number of staggered rod schemes were examined, a typical plot of the axial power profile through the column of sticks *i* =1 at an ECP Group 1 60 %, Group 2 45 % and Group 3 20 % is shown in Figure 6.

3.3 Transient Responses

Prior to examining the predicted response to transients such as flow reductions the sensitive to the selected time step was examined. Within M32 the time step is set automatically, however, a user input acceleration factor is available. An acceleration factor of unity will produce the shortest possible time steps in M32. The effect of varying this factor on the predicted start up rate (in decades per minute) when the step like removal of a control rod is simulated can be seen in Figure 7.

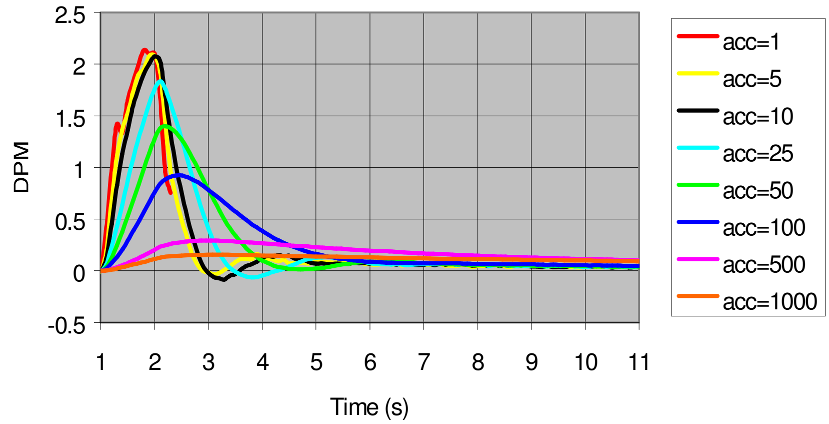

Figure 7 M32 transient response with varying acceleration factor

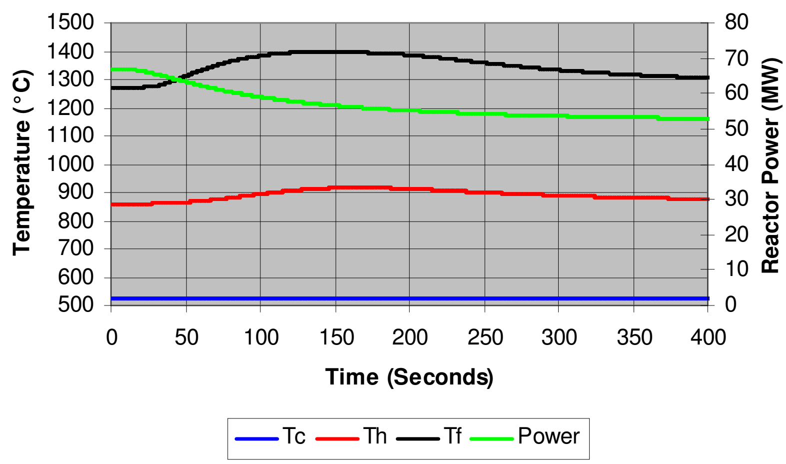

Figure 8 Proposed designs predicted response to a flow reduction

The proposed cores response to a number of transients was simulated. Shown in Figure 8 is the predicted response, with an acceleration factor of 25, to a step like flow reduction from 40 kg s^{-1} to 30 kg s^{-1}.

4. Conclusion

Whilst acknowledging the limitations of M32 it does however provide a useful educational tool to 'practically' investigate the design of reactor cores. Many of the necessary stages in the design process are illustrated. From initial nuclear data preparation and thermal hydraulic characterization to whole core transient analysis are illustrated.

This work has demonstrated both the feasibility of the proposed design and the application of a computational tool such as M32. Although in no way a replacement for industry standard coupled methods, M32 provides a useful addition to a portfolio of tools for education and training in reactor design methodologies. If the required input data is readily available the code is easy to implement on most standard PCs. However, if a relatively complex core such as the GT-MHR, is to be modeled then external sophisticated lattice codes are required to generate the necessary nuclear data.

Disclaimer

Any views expressed are those of the authors and do not necessarily represent those of the Nuclear Department, Flagship Training Ltd or those of Her Majesty's Government

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