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RSMASS: A SIMPLE MODEL FOR ESTIMATING REACTOR AND SHIELD MASSES

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ABSTRACT

A simple mathematical model (RSMASS) has been developed to provide rapid estimates of reactor and shield masses for space-based reactor power systems. Approximations are used rather than correlations or detailed calculations to estimate the reactor fuel mass and the masses of the moderator, structure, reflector, pressure vessel, miscellaneous components, and the reactor shield. The fuel mass is determined either by neutronics limits, thermal/hydraulic limits, or fuel damage limits, whichever yields the largest mass.

RSMASS requires the reactor power and energy, 24 reactor parameters, and 20 shield parameters to be specified. This parametric approach should be applicable to a very broad range of reactor types. Reactor and shield masses calculated by RSMASS were found to be in good agreement with the masses obtained from detailed calculations.

INTRODUCTION

Since launch costs are expected to be a major consideration for any space-based power system, reasonable estimates of the power system masses are essential to identify promising concepts and technologies. Codes are being developed (Edenburn, 1987 and Juhasz, 1987) that will allow rapid mass estimates to be made for a variety of systems over a broad parameter range. For this purpose, a simple reactor and shield mass model (RSMASS) was generated to be used as a subroutine in the system codes for nuclear powered concepts. This model can also be used, independent of the system code, to perform reactor/shield mass parameter studies, to compare different types of reactors and to check mass estimates for specific proposed reactors and shields.

Several approaches were considered for the reactor and shield mass model. Detailed calculations would require far too much calculational time to permit many parameter studies; on the other hand, simple correlations with power would be too crude for the intended purposes. The RSMASS model uses an intermediate approach based on simple approximations rather than correlations or detailed calculations. Since the reactor mass is typically a small fraction of the total power system mass for multimegawatt power systems, an approximate approach should be suitable for our purposes.

APPROACH

Reactor Mass

The sequence used to compute the reactor mass is to first compute the uranium fuel mass and then compute the mass of all other reactor components. This approach is required since the mass of all other reactor components is dependent on the fuel mass. The reactor fuel mass will be determined by either neutronic limits (burnup plus criticality), thermal hydraulic limits, or fuel damage limits (maximum burnup fraction), whichever yields the largest mass. The most important equations used in this model are presented in the following; their derivations are given by Marshall (1986).

- Fuel Mass-Neutronic Limit

The equation for the initial critical mass is given by

$$M_C^O = \frac{C_M M_C^C}{\varepsilon^2}\left(\frac{13,600}{VF\rho_F}\right)^{1.5} ,$$

where M_C^O = initial critical U mass (kg),

ε = fractional fuel enrichment,

M_C^C = critical mass for compact, reflected fully enriched UC sphere (kg of U^{235}),

C_M = correction factor for absorbers, etc.

VF = fuel volume fraction of core, and

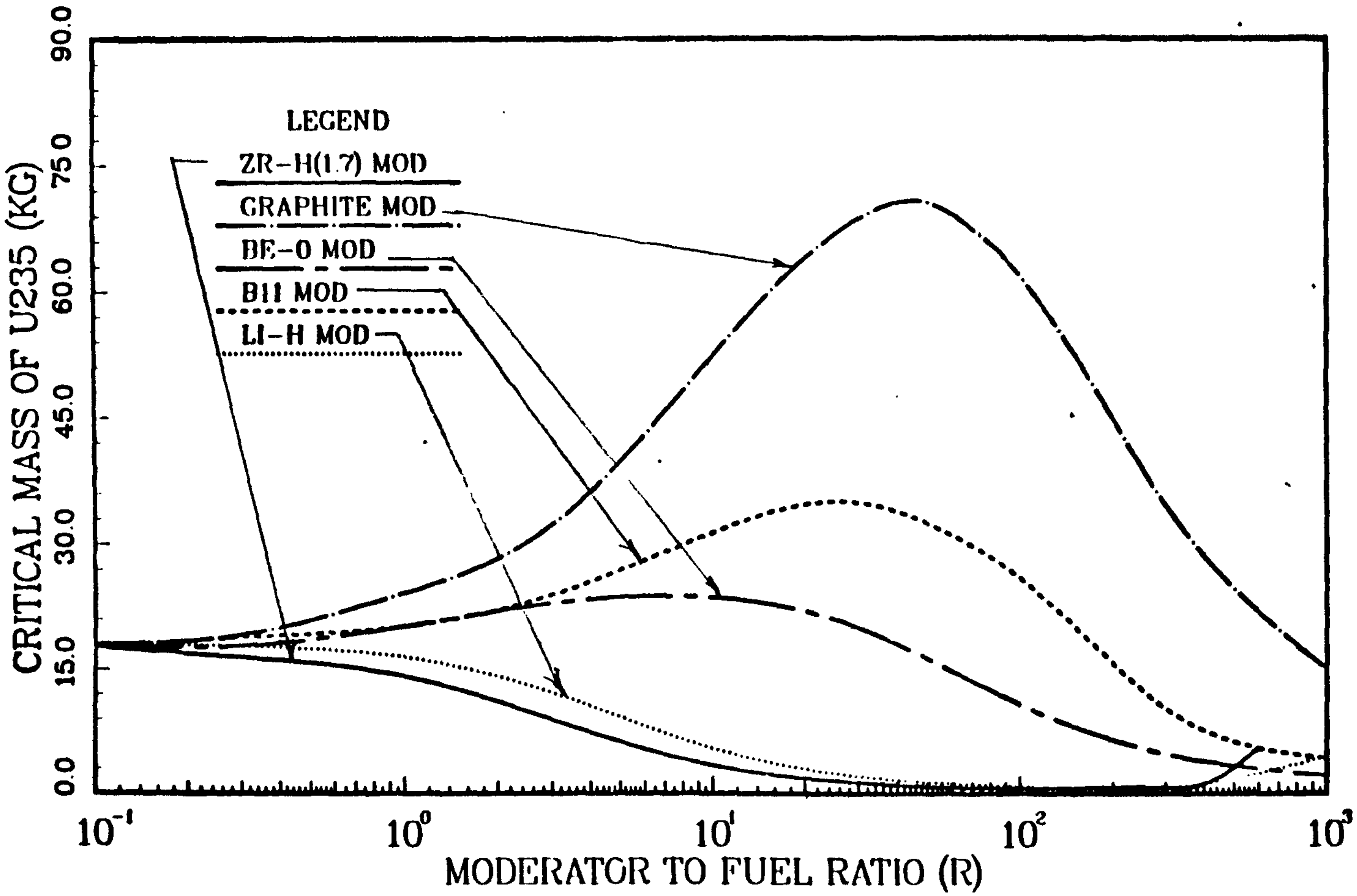
ρ_F = unhomogenized fuel density (kg/m^3).

The initial critical fuel mass (M_C^O) is determined by applying corrections to the uranium mass of a compacted, reflected critical sphere of 93% enriched uranium carbide and moderator. The critical fuel mass for compacted, reflected spheres (M_C^C) was obtained from transport theory computer calculations (McDaniel and Harris 1983 and Alcouffe et al., 1984) and is provided as a family of curves as a function of the moderator-to-fuel molecular ratio for several choices of moderator (Fig 1). The use of uranium carbide in these calculations was arbitrary; a review of several fuel compounds

FIGURE 1

CRITICAL MASS OF U235 VS MOD. TO FUEL RATIO

(For Compacted Spheres of UC and Moderator, fully Enriched, with 10 cm BeO Relector)



$$\frac{\text{Molecules of Moderator}}{\text{Atoms } U^{235}}$$

has shown that the critical fuel mass is not strongly dependent on the molecular composition of the fuel. A 10-cm thick BeO reflector is assumed in these calculations. For very low moderator-to-fuel ratios, the family of curves converge to the critical mass corresponding to a compacted, reflected fast reactor. Mass corrections for lower enrichment and lower densities (voids and non-fuel materials in core) are computed by RSMASS in the equation given above. Corrections for heterogeneities, parasitic absorbers, and other considerations must be computed external to RSMASS and entered as a correction factor (C_M). In most cases C_m = 1.0 is a good approximation. The correction for enrichment was derived only for fast reactors and may not be a good approximation for thermal reactors; however, in most cases we are interested in the minimal fuel mass and full enrichment is assumed in these calculations (i.e., no enrichment correction is required).

In order to provide power over the life of the reactor, uranium-235 must be consumed. The total uranium required for burnup is

$$M_B = \frac{0.38E}{\varepsilon e} \quad .$$

where M_B = U mass required for burnup (kg),

E = Energy (MWe • years),

e = net fractional efficiency.

Since burnup will reduce the enrichment at the end of life, the critical mass at the end of life will be greater than the initial critical mass. The end-of-life critical mass can be estimated from

$$M_C = \frac{M_C^O + \sqrt{{M_C^O}^2 + 4M_C^O M_B(1 - \varepsilon)}}{2} \quad .$$

Consequently, the total U mass required to achieve criticality throughout the life of the reactor is just the sum of the uranium required for burnup and the uranium required for criticality at end of life.

$$M_E = M_C + M_B .$$

where M_E = total U mass required based on neutronic limits (kg).

•<u>Fuel Mass -- Thermal Hydraulic Limit</u>

Although very large quantities of power can be obtained from small quantities of uranium, heat transfer from the fuel to the coolant and temperature limits on the fuel, cladding, and coolant will place a limit on the specific power for a reactor. This limit will depend on the fuel, geometry, coolant, etc. The mass of uranium required based on thermal/hydraulic limits is

$$M_P = \frac{PP_F}{P_S e} ,$$

where M_P = U mass required based on thermal/hydraulic limits (kg),

P = maximum reactor power (MWe),

P_F = core spatial peak/avg. power factor,

P_S = specific power limit (MW_{th}/kg U), and

e = net efficiency.

The maximum permitted specific power (P_S) is calculated, external to RSMASS, as a function of important parameters for each reactor configuration. Simple thermal/hydraulic models (e.g., Dobranich, 1987) are used to obtain the specific power limit data.

•<u>Fuel Mass--Fuel Damage Limit</u>

Although there may be adequate fuel present to provide the needed energy for a reactor, there will normally be a limit placed on the fraction of fuel that can be burned up. This limit is based on fuel damage and gas release considerations for a particular design and operating conditions. The mass of uranium required based on fuel damage limits is

$$M_F = \frac{0.38\ EP_F}{\beta e} ,$$

where M_F = U mass required based on fuel damage limit (kg), and

β = maximum permitted uranium burnup fraction. (Atoms of uranium fissioned per cm^3/total number of initial uranium atoms per cm^3.)

•Limiting Uranium Mass

The mass of uranium required for any reactor system will be the largest of the three masses based on the three potential limits; i.e.,

$$M_L = \text{greatest of } M_E, M_P, \text{ and } M_F.$$

•Other Reactor Component Masses

Once the fuel mass has been determined, it is a fairly simple exercise to estimate the mass of the other reactor components. The other components are listed below along with a description of what the component mass estimate is based on.

Component	Estimate Based On
Moderator (M_m)	desired moderator-to-fuel ratio
Structure (M_s)	approximate volume ratio of structure to fuel plus moderator
Reflector (M_{RF})	core size, reflector thickness
Pressure Vessel (M_{pv})	core size, coolant pressure, pressure vessel material
Miscellaneous Components (M_{MIS})	mass of actuators, instrumentation, etc., is assumed to be approximately equal to the fuel plus moderator mass.

•Total Reactor Mass

The total reactor mass is the sum of all the component masses

$$M_R = M_L + M_m + M_s + M_{RF} + M_{PV} + M_{MIS}.$$

Shield Mass

•Neutron Shield Thickness

The thickness of the neutron shield can be estimated from

$$t_n = \frac{-\ln\left[\dfrac{(1.5 \times 10^{-17}) D_n r R_P^2 \Sigma_C e}{E}\right]}{100\Sigma_r}$$

(for $t_n \leq 0$: $t_n = 0$).

Here, t_n = initial neutron shield thickness (m),

r = reactor radius (m),

E = energy (MWe • years),

D_n = max allowed payload neutron dose (nvt),

e = net fractional efficiency,

R_p = payload separation distance (m),

Σ_C = core macroscopic self-absorption cross section (cm^{-1}), and

Σ_r = shield macroscopic neutron removal cross section (cm^{-1}).

This assumes that no neutrons are absorbed by the gamma shield.

The neutron shield thickness estimates are based on the familiar $\frac{1}{R_p{}^2}$ and $e^{-\Sigma rt}$ approximations. Although the approximate relationship described above should provide a reasonable estimate of the relative influence of variations in the important parameters, this approach is not very reliable for determining the absolute value for the shield thickness. A much more reliable approach would require very time consuming, detailed Monte Carlo calculations that would be impractical for our purposes. In order to provide reasonable accuracy while maintaining the simplicity of the above approach, the results of a detailed Monte Carlo calculation were used to normalize the RSMASS shield calculations. The (1.5×10^{-17}) term in the above equation is the normalization constant obtained from a Monte Carlo calculation; this term also accounts for a conversion of units.

•Gamma Shield Thickness

Since the neutron shield will also attenuate gammas, the neutron shield-gamma attentuation ($\mu_n t_n$) must first be subtracted out. The required gamma shield thickness is then given by

$$t_{\gamma,O} = \left(\frac{-1}{\mu_\gamma}\right)\left(\frac{\ln\left[\frac{D_\gamma \mu_c r R_p^2 (1.0 \times 10^{-9}) e}{E}\right]}{100} + \mu_n t_n\right)$$

(for $t_{\gamma,O} < O$: $t_{\gamma,O} = O$),

where $t_{\gamma,O}$ = first iteration gamma shield thickness (m),

μ_γ = gamma shield γ-attenuation coefficient (cm^{-1}),

μ_n = neutron shield γ-attenuation coefficient (cm^{-1}),

μ_c = core γ-attenuation coefficient (cm^{-1}), and

D_γ = max allowed payload gamma dose(R).

For this calculation, it is assumed that a single energy group can be used to estimate the attenuation of gammas for all energies. A preliminary comparison with detailed calculations suggests that attentuation coefficients for 3 MeV gammas are a fair approximation as long as the gamma spectrum from the core and the spectral dependence of the gamma shield attenuation coefficient are not appreciably different from the values used in the normalization calculation. The (1×10^{-9}) term in this equation is the normalization constant for gamma shielding obtained from a Monte Carlo calculation; this term also accounts for the conversion of units.

Also, for the derivation of this equation it was assumed that any gamma photon colliding with the shield material will not reach the payload. For thick shields, however, multiple collisions can scatter a fraction of the photons back to payload, building up the dose at the payload. This dose buildup can be accounted for by first computing the total gamma optical thickness of the shield as

$$\mu t_{t,o} = (\mu_n t_n + \mu_\gamma t_{\gamma,o})100$$

and then computing the buildup factor:

$$B_o(\mu,t) = A_1 \exp(-a_1 \mu t_{t,o}) + (1 - A_1) \exp(-a_2 \mu t_{t,o})$$

where

t_t = total shield thickness (m),

$B_o(\mu,t)$ = gamma does buildup factor, and

A_1, a_1, a_2 = known buildup factor constants.

The buildup factor is then inserted back into the gamma shield thickness calculation and, after several iterations, the final gamma shield thickness is determined.

- <u>Neutron/Gamma Shield Thickness Iteration</u>

Now that the gamma shield thickness has been computed, the neutron shield thickness is recalculated to account for the neutron shielding by the gamma shield. One more iteration is then performed to account for gamma shielding by the neutron shield and neutron shielding by the gamma shield to get the final shield thickness.

•Shield Mass Calculation

The assumed shadow shield geometry for this model is presented in Figure 2. Two gamma shields and two neutron shields are permitted, and the user may specify the fractional split of the thickness between the first and second gamma shield and between the first and second neutron shield. The user may also specify the cone half angle, the location of the shield relative to the core, and the shield materials. Once the thickness has been calculated, it is a straightforward task to compute the shield mass based on the assumed geometry and desired shield materials. Geometry correction factors can also be used to account for deviations from a shadow shield geometry, including 2π, 4π, shaped 4π shields, etc.

•Comparison with Detailed Calculations

A comparison has been completed of the reactor/shield masses obtained from detailed calculations by the proposers of space power reactors with the masses calculated by RSMASS for these proposed reactors. An initial goal for agreement between RSMASS calculated masses and the masses obtained from detailed calculations was chosen to be a factor of two. Discrepancies greater than a factor of two would be indicative of either a modeling deficiency by RSMASS, an inappropriate parameter choice for RSMASS, or an error in the detailed calculations.

Figure 3 compares the RSMASS reactor/shield masses for liquid-metal-cooled reactors with the masses calculated by various laboratories for their proposed reactors. Except for the Rockwell SP-100 reactor, all of the reactors are for MMW power. Good agreement is observed for all of the proposed reactors. A similar comparison was made for thermionic reactors. The two cases shown in Figure 4 are General Atomic's (GA) SP-100 and their 2 MW "growth" design. Again, the agreement is good. (A direct comparison of these thermionic reactor masses with masses for other types of reactors may be misleading since these designs have not been optimized for MMW requirements. Also, a system mass analysis is required to evaluate the net mass impact of thermionic reactors relative to other concepts since the thermionic reactor mass also includes the power conversion system mass.)

Figure 5 compares the reactor/shield masses for Brookhaven National Laboratory's (BNL) gas-cooled reactors with the masses calculated by RSMASS. It should be pointed out that the calculated gas-cooled reactor masses appear to be very sensitive to the reactor input parameter choices and some values for gas-cooled reactor parameters are only an educated guess at this time (such as the moderator-to-fuel ratio, the critical mass correction factor, and the specific power limit). Nonetheless, the RSMASS calculated reactor mass is in

RSMASS ASSUMED SHIELD GEOMETRY

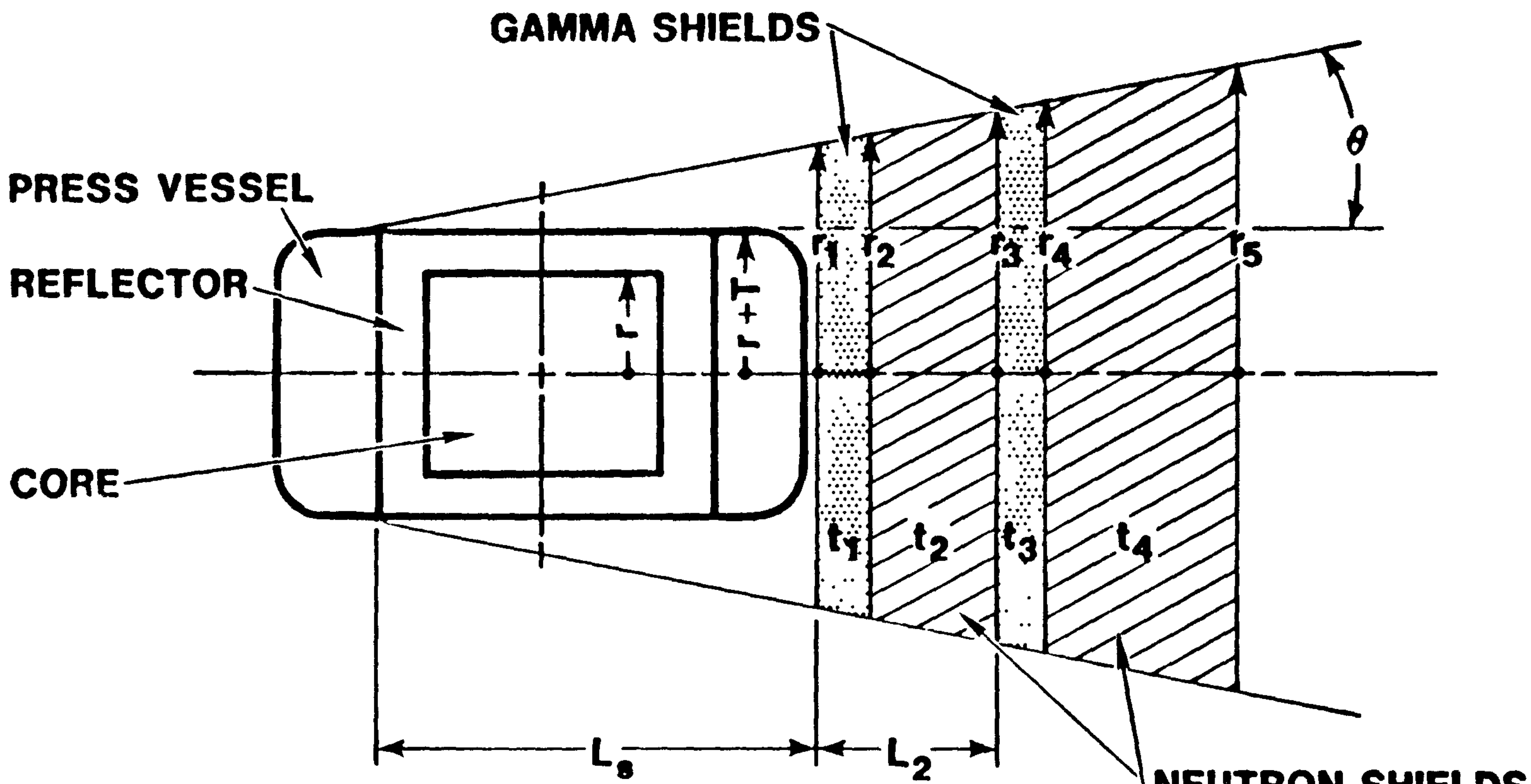


Figure 2. RSMASS Assumed Shield Geometry

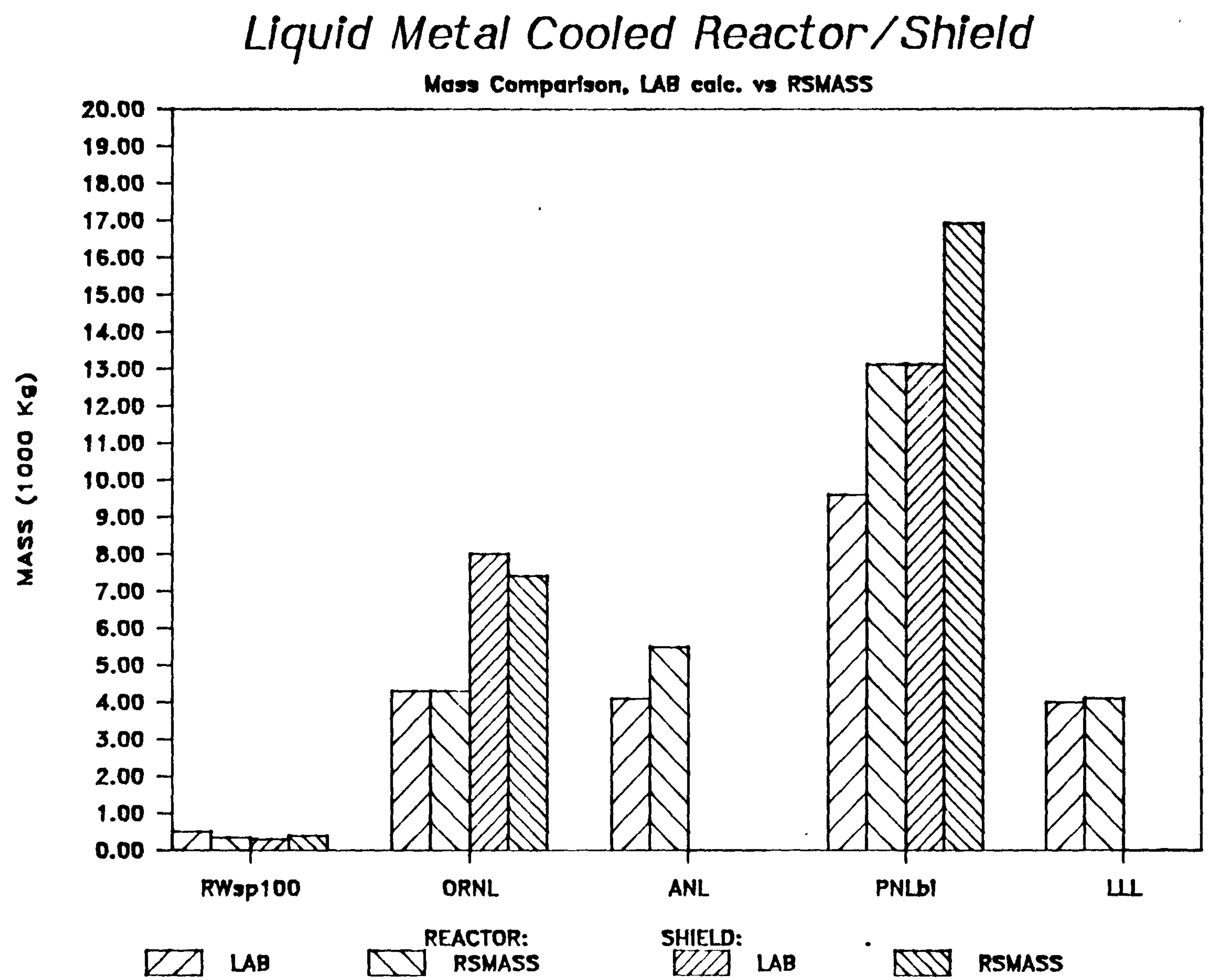


Figure 3. Liquid Metal Cooled Reactor/Shield

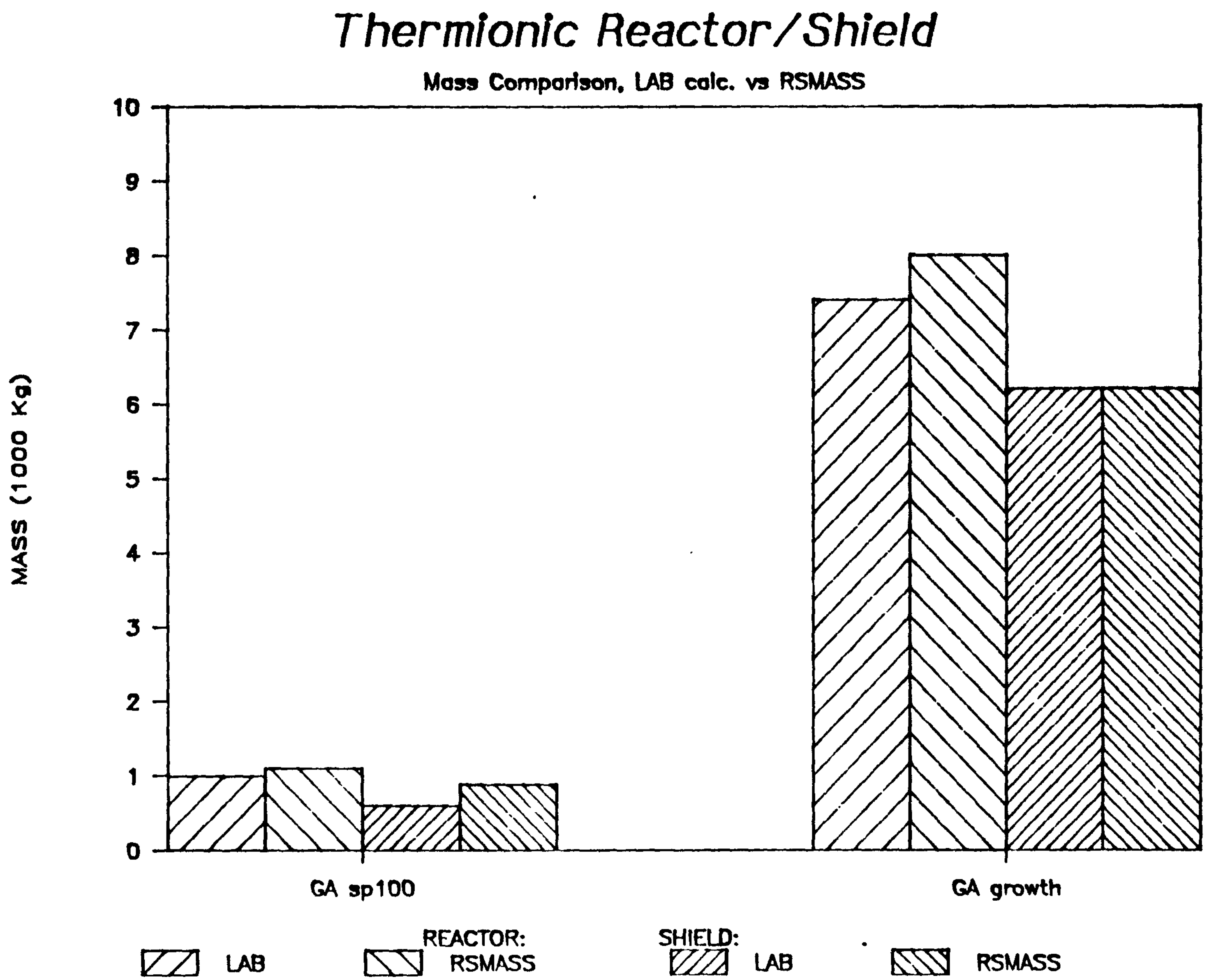


Figure 4. Thermionic Reactor/Shield

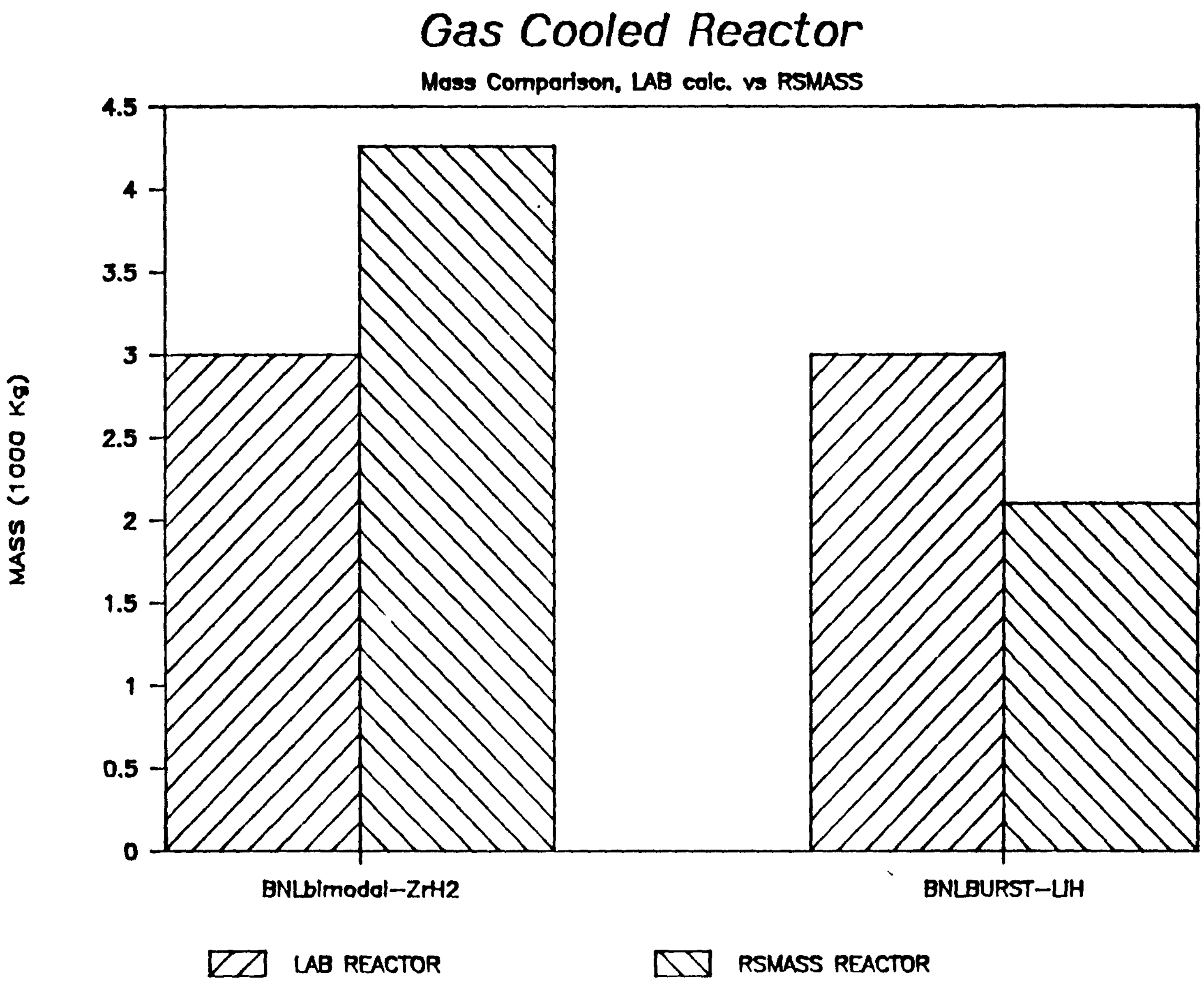


Figure 5. Gas Cooled Reactor

good agreement with BNL's masses for both the $ZrH_{1.7}$ moderated bimodal concept and the LiH moderated burst mode reactor concept.

A number of other comparisons and studies are now under way. In some instances RSMASS has uncovered oversights in the more detailed calculational efforts. RSMASS is also providing some insights into the mass advantages and disadvantages for the various concepts as a function of operating conditions and as a function of important parameters (such as fuel density).

•Conclusion

RSMASS can provide good estimates of reactor and shield masses for a broad variety of reactor concepts proposed for MMW space power applications. These estimates will probably not be more than 50% different from masses computed using more detailed and time consuming calculation methods; the agreement is much better than our original goal. It must be emphasized, however, that the 50% uncertainty refers to the uncertainty in the model and not the basic input data. For example, the specific power data for liquid-metal-cooled reactors depends strongly on the coolant outlet temperature, the assumed fuel characteristics, and a number of other factors. The uncertainty in this basic data may not be resolved until years of design and development work have been completed and the magnitude of the uncertainty in the data can be much greater than the model uncertainty.

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