

# Mass Estimates of Very Small Reactor Cores Fueled by Uranium-235, U-233 and Cm-245

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**Abstract.** This paper explores the possibility of manufacturing very small reactors from U-235, U-233 and Cm-245. Pin type reactor systems fueled with uranium or curium metal zirconium hydride (UZrH or CmZrH) are compared with similar designs using U-235. Criticality measurements of homogeneous water uranium systems, suggest that reactor subsystem masses have a broad minimum for hydrogen-to-uranium atom ratios that vary from 25- 250. This paper compares the masses of metal-hydride fueled reactor systems that use U-235, U-233, and Cm-245 fuel with hydrogen-to-metal atom ratios from 20-300 when cooled by gas (HeXe), liquid metal (Na), and water. The results indicate that water cooled reactors in general have the smallest reactor subsystem mass. For gas and liquid-metal cooled reactors U-233 subsystems have total masses that are about ½ those of similarly designed U-235 fuel reactors. Reactor subsystems consisting of 11.2 % enriched Cm-245 (balance Cm-244) that can be obtained from fuel reprocessing have system masses comparable to that of U-233. The smallest reactor subsystem masses were on the order of 60-80 kg for U-233 fueled water cooled reactors.

## INTRODUCTION

Very small compact reactors will have great utility as power supplies for ambitious space missions to the outer planets or as portable or transportable power sources on the surface of planets. This paper explores the possibility of using alternative fissionable isotopes such as U-233 and Cm-245 for small space reactors. For this paper, only pin type reactor systems fueled with uranium or curium metal zirconium hydride (UZrH or CmZrH) were considered. Other fuel forms and chemical compositions are of course possible including plate type fuels (or particle bed fuels) made from carbides, oxides or metal based dispersion fuels. For very small reactors that do not require high power, it is highly likely that these alternative geometry configurations could produce compact reactor designs as small or smaller than those presented here. Nevertheless, in the interest of time, this paper restricts itself to pin type reactors that use metal hydride dispersion fuel.

## SMALL IDEAL CRITICAL SYSTEMS

The nuclear criticality safety community has collected a large amount of data in the effort to preclude inadvertent assembly of critical systems. This information most often describes the amount of U-235 or other fissile material that is required to form a critical mass in various geometries and moderator mixtures. This data has been used here to estimate the size and configuration of minimum mass reactor subsystems. Generally two types of critical systems are considered that represent the extremes of reactor fuels under consideration. One extreme is a critical system that is an optimally water moderated system (solution type

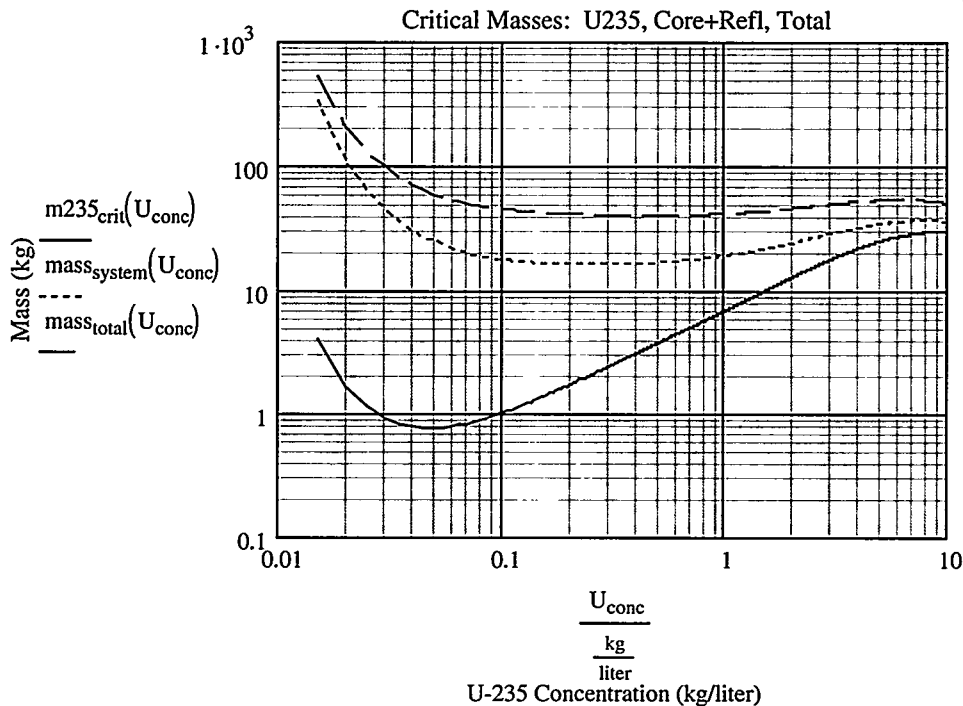
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reactor or dilute uranium lattice in water). Because this reactor has an effective neutron moderator (hydrogen) it will generally lead to systems having **minimum mass of U-235**. The second extreme consists of a spherical metal reactor that is water reflected. This type reactor will generally have the **minimum size**. This information is conveniently represented as a curve of mass versus hydrogen to metal atom ratio in Figure 1 (Knief 1988). The critical mass of U-235 for a water-moderated reactor with a 25mm reflector is shown as the red (solid) curve. For uranium concentrations less than about 0.3 kg-U/liter this type of reactor is typically a solution reactor of  $UO_2F_2$  dissolved in water to the desired concentration. Note that only 780 g of U-235 are required to make the system critical for fully enriched uranium concentrations near 0.05 kg/liter. A reactor of this configuration would have a diameter of about 42-45 cm. For uranium concentrations above ~5 kg/liter the reactor is approaching a water reflected bare-metal system configuration. For intermediate uranium concentrations (0.1 – 2 kg/liter) above about 0.2 kg-U/liter the reactor can be configured as an array of uranium fuel plates or pins moderated by water.



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**FIGURE 1.** Critical mass and system masses for spheres of homogeneous water-moderated and water-reflected U-235 solutions. Red (solid) curve shows the critical mass. Blue (dotted) curve shows the estimates of the solution mass plus the 25 mm water reflector. Black (dashed) curve shows the total system mass including a 1 cm thick nickel alloy containment with average density of 8 kg/liter.

Estimates for the combined mass of the uranium plus water solution mass and the 25 mm water reflector are also shown in Figure 1 as the blue curve. The combined masses were estimated by assuming that the volume fraction of the uranium is small and that the water solution weighs 1 kg/liter. The total mass is shown in black (dashed) and assumes a 1cm thick pressure vessel having a density of 8 kg/liter. Notice that the core + reflector + pressure vessel mass (black curve) has a broad minimum from 0.1 to 2.0 kg/liter. Systems of this configuration typically have a diameter of 30 cm and a core + reflector mass of 20 kg.

It is assumed here that this figure generally represents the situation for a wide variety of reactor designs. If this is the case, then there are a number of observations that one should conclude:

1. Reactors subsystems are most likely to have the least mass if they use hydrogen as a moderator,
2. The total reactor subsystem mass minimum is broadly distributed over a range of hydrogen-to-fissile metal atom ratios and results in reactor subsystem masses of 40-50 kg for a water moderated solution reactor, and

- The reactor subsystem mass will be minimized at uranium concentrations of 0.2 – 2 kg/liter which is equivalent to hydrogen-to-metal atom ratios 10-100.

Of course a complete nuclear power system must include the mass of the shield, power conversion subsystem, and the heat rejection unit. None of which are included in this paper. Nevertheless the data presented above represents the situation for an ideal solution reactor or a water lattice reactor. It indicates that the minimum mass is near 40-50 kg. Any practical reactor will have to include reactor structural components and select fuel configurations and materials consistent the power conversion system that it is to be coupled to the reactor. The addition of other materials or voids will greatly increase the minimum practical mass that a reactor can be designed to. As a rule-of-thumb the critical mass of a system increases roughly proportionally to  $1/\text{density}^2$  (Paxton 1986). Thus, assuming that all other design options remain constant, the dilution of fuel by a factor of 30-40% will nearly double the critical mass having a similar effect on the total system mass. These practical considerations are taken into account in the next section.

## CONFIGURATION OF UZRH PIN TYPE REACTORS

The section above suggests that reactors having hydrogenous moderators are likely to have smaller masses those that do not. It further suggests that hydrogen-to-fissile metal atom ratio should be on the order of about 30/1. The use of UZrH as fuel allows for the inclusion of hydrogen in a reactor core while still permitting operating at relatively high fuel temperatures (up to 750 C). The SNAP-10a reactor, the only US reactor that has flown in space, used this fuel type (Johnson 1967 & Anderson 1983). Because one of the purposes of this report is to identify reactor subsystems having minimum mass and to explore the possible mass reductions that one might achieve by replacing U-235 with U-233 or even Cm-245, we have restricted our investigations to ZrH dispersion fuels placed in stainless steel fuel pins. In this report reactor subsystem mass includes fuel pins, cladding, moderator, coolant, structure, radial and axial reflector, pressure vessel, and control mechanisms (10 kg).

### Enrichment and Weight Percent

For  $\text{ZrH}_x$  based dispersion fuels, the primary design variables are weight percent fissionable material, enrichment of fissionable material, fissionable isotope, and hydrogen stoichiometric ratio  $x$ . Other parameters such as pitch and fuel pin diameter are also important; however, their selection is strongly influenced by heat transfer and fluid dynamic limitations. The hydrogen stoichiometric ratio was selected at 1.65 because this UZrH is single phase over the temperature range of interest, and because the hydrogen vapor pressures are not too large at the maximum allowable fuel temperatures of 750 C. Table 1 lists the weight percents ranges investigated and the enrichments used for the various fuels.

**TABLE 1. Weight percent and Enrichment of Fissionable Isotopes for  $\text{ZrH}_{1.65}$  Dispersion Fuel.**

Fissionable Isotope	Weight % Fissionable Metal	Enrichment of Fissionable Isotope
U-235 / U-238	10-45	93.15
U-233 / U-234	10-45	98.13
Cm-245/ Cm-244	10-45	10

The upper range of Uranium or other heavy metal atom used in the ZrH fuel was set at 45w%. This value was selected because it is believed to be near the upper limit at which acceptable metallurgical and mechanical properties can be maintained. It is also the weight percent used in many of the Low Enrichment Uranium (LEU) replacement cores (UZR-27). The U-233 isotope is assumed to be enriched to 98.13 percent. This value was selected as it was used in Paxton (1986). The Curium isotopic composition was based on information provided by Benedict (1981). Table 2 lists the isotopic composition of Cm produced in a 1000 MWe PWR with self-generated Pu recycle. All nuclides but Cm-244 and Cm-245 have relatively short half-lives. If the Cm is obtained from existing sources of PWR fuel, then the isotopic ratio of Cm-245 will be approximately 10%. (Note that the calculations actually used 11.2% rather than 10%. This difference probably makes little or no difference in the results.)

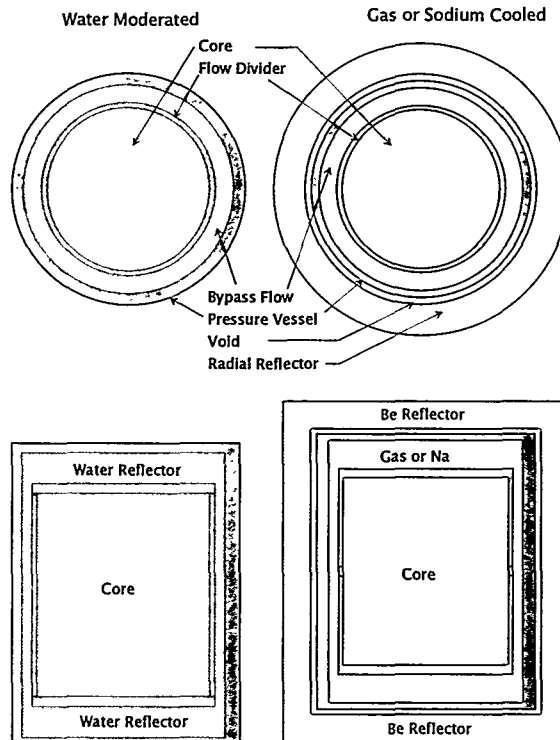
**TABLE 2. Isotopic composition of Cm produced in a 1000 Mwe PWR with self-generated Pu recycle (Benedict 1981) 60 days after discharge.**

Nuclide	Kg/Yr	Half-life	Ratio of Nuclide to total
Cm-242	0714	163 days	0.039
Cm-243	0.00861	32 yr	4.7e- 4
Cm-244	15.6	17.6 yr	.857
Cm-245	1.74	9300 yr	0.096
Cm-246	0.174	5500 yr	0.0096

## Neutron Transport Calculations and Reactor Geometry

Reactor criticality neutron transport calculations were performed with the MCNP4b code (Briesmeister 1997), and the mass of the reactor was estimated by summing all the masses of the components. In all cases the reactor fuel consisted of a hexagonal array of fuel pins located in a core barrel (flow divider) surrounded by a bypass flow region. Three types of reactors were examined, water-cooled, gas-cooled and sodium-cooled. For each type of reactor the three fissile isotopes of fuel U-235, U-233 and Cm-245 were used. Figure 3 illustrates axial and longitudinal cuts of the reactor geometries used in the criticality calculations. The water-cooled reactor used the bypass flow region as the radial reflector. Both the sodium and gas-cooled reactors used external Be radial and axial reflectors that were 35 and 25 mm respectively. In all cases the pressure vessel was assumed to be 9 mm thick.

The results of the calculations are presented Table 3 and summarized in Figure 4. Typically these calculations were performed by running MCNP4b with a given geometry, and then increasing or reducing the radius and height of the core to make the system critical with excess  $k_{eff}$  of about 0.02-0.09. Because the size and mass of the reflector, pressure vessel, and grid plate were keyed to the radius of the core, the total system mass would increase or decrease based primarily on the size of the core. Table 3 lists details



**FIGURE 2. Axial and longitudinal cross sections of the MCNP4b transport geometry.**

for the important variables used set up the geometry and to define the atom concentrations of various isotopes. Figure 4 summarizes the results of these calculations by plotting the total system mass as a function of hydrogen to metal ratio. The smallest mass system is a U-233 fueled water moderated reactor system. This system weighs 60 kg total and has 2.53 kg of U-233. Another very compact reactor is the U-233 fuel gas cooled reactor. It has a total system mass of 109.2 kg. A breakdown of the mass distribution

for these two systems is listed in table 4. The major difference between these two systems is the mass of fuel and reflector required in the gas-cooled system. Also observe that the predicted reactor mass for a U-235 fueled sodium cooled reactor was about 200 kg, very close to the actual mass of SNAP-10A (220 kg, Johnson 1967).

**Table 4: Mass distribution in a U-233 water cooled and gas cooled reactor subsystem.**

Reactor Subsystem	Water/Gas	Clad	Fuel	Reflector	Pres. Ves.	Structure	Control	Total
U-233 Water Uzrhg23_a.i	5.1 kg	2.0 kg	5.8 kg	8.1	25.2	4.1	10	60.3
U-233 Gas Uzrhg23_b.i	0.1	3.8	36.5	31.9	23.0	3.9	10	109.2

Case Filename	r.fuel (mm)	r.clad (mm)	pitch (mm)	npins	r.core (cm)	L.fuel	k.eff	rho.fuel	Mass (kg)			t.refl(h2o)			w%U	HU235%	Lpv (mm)	Generato n Time (usec)
									Fissile Isotope	m.fuel (kg)	M.total (kg)	t.refl(h2o) (cm)	(cm)	(cm)				
<b>WATER</b>																		
mU235																		
zrhw25_a	2.95	3.4	13.8	274	12	30	1.25	8.248	7.7	18.6	101	3.5	2.5	45	23.3	9	10.6	
zrhw25_b	2.95	3.4	12.8	267	11	28	1.015	8.248	7.08	16.9	89.4	3.5	2.5	45	20.2	9	11.5	
zrhw25_c	2.45	2.9	13.8	267	11	28	0.996	8.248	4.2	10.8	82.2	3.5	2.5	45	33.4	9	16.8	
zrhw25_d	1.95	2.4	13.8	267	11	28	0.96	8.248	2.66	6.36	78.4	3.5	2.5	45	52	9	22.9	
zrhw25_e	1.95	2.4	13.8	267	12	28	0.981	8.248	3.16	6.36	86	3.5	2.5	45	52	9	23.4	
zrhw25_f	2.95	3.4	13.8	274	12	28	1.05	8.248	7.2	17.3	96.6	3.5	2.5	45	23.3	9	13	
zrhw25_g	2.95	3.4	12.8	267	11	28	1.021	8.248	8.1	19.3	91.8	3.5	2.5	45	17.9	9	10.6	
zrhw25_c	2.45	2.9	13.8	252	11.5	28	1.029	8.248	4.6	11	86.7	3.5	2.5	45	33.4	9	16.8	
mU233																		
zrhw23_a	2.45	2.9	13.8	154	9	24	1.025	8.248	2.53	5.76	60	3.5	2.5	45	31.5	9	11.1	
zrhw23_b	2.45	2.9	13.8	154	10	24	1.04119	6.299	0.796	5.43	65.8	3.5	2.5	15	127.6	9	13.4	
zrhw23_c	1.45	1.9	11.8	375	12	26	0.994	6.299	0.595	4.058	80.5	3.5	2.5	15	257	9	25.1	
zrhw23_d	7.45	7.9	17.8	114	10	24	1.0812	6.299	4.423	30.2	88.2	3.5	2.5	15	30.5	9	4.6	
zrhw23_f	2.45	2.9	11.8	241	10	20	1.05835	8.248	3.564	8.104	63.9	3.5	2.5	45	23.1	9	8.1	
zrhw23_g	2.45	2.9	11.8	260	10	24	1.0173	8.248	1.498	3.407	64	3.5	2.5	45	64.5	9	17.2	
zrhw23_e	2.45	2.9	7.8	241	8	24	0.9	8.248				3.5	2.5	45	66.8	9		
mCm245																		
zrhw65_a	1.45	1.9	11.8	375	12	26	1.06652	8.288	0.269	5.34	81.8	3.5	2.5	45	588	9	43.2	
zrhw65_b	1.45	1.9	11.8	375	12	26	1.45	8.288	1.719	4.107	71	3.5	2.5	45	70.8	9	21.3	
zrhw65_c	5.45	5.9	13.8	190	10	22	1.269	8.288	1.63	32	89	3.5	2.5	45	67.5	9	8.5	
zrhw65_c	5.45	5.9	13.8	122	8	20	1.09932	8.288	0.95	18.8	67	3.5	2.5	45	67.5	9	10.0	
<b>GAS</b>																		
mU235																		
zrhg25_a	10.05	10.5	23	176	16	32	1.0853	6.06	10.05	108	240	5	2.5	10	40.4	9	7.4	
zrhg25_b	10.05	10.5	23	155	15	32	1.0558	6.299	12.9	92.5	211	5	2.5	15	25.4	9	5.2	
zrhg25_c	10.05	10.5	23	155	15	32	1.06824	6.577	17.9	96	215	5	2.5	20	17.9	9	3.7	
mU233																		
zrhg23_a	10.05	10.5	23	98.7	12	24	1.0403	6.06	4.47	45.6	128	5	2.5	10	38	9	5.2	
zrhg23_b	10.05	10.5	23	83	11	22	1.032	6.299	5.37	36.5	109	5	2.5	15	23.9	9	3.34	
zrhg23_c	10.05	10.5	23	83	11	22	1.0658	6.557	7.45	38	110	5	2.5	20	16.8	9	2.4	
mCm245																		
zrhg65_a	10.05	10.5	23	98.7	12	24	1.043	6.06	0.513	45.6	128	5	2.5	10	348	9	16.6	
zrhg65_b	10.05	10.5	23	83	11	22	1.085	6.852	1.115	39.69	112	5	2.5	25	116	9	7.4	
zrhg65_c	10.05	10.5	23	83	10	20	1.04	8.288	1.824	39.69	99.3	5	2.5	45	47	9	3.8	
<b>SODIUM</b>																		
mU235																		
zrhna25_a	10.05	10.5	22	145	14	28	1.08772	6.06	7.36	79.1	188	5	2.5	10	40.4	9	7	
zrhna25_b	10.05	10.5	22	145	14	28	1.09302	6.299	11.47	82.2	191	5	2.5	15	25.4	9	4.7	
zrhna25_c	10.05	10.5	22	127	13	26	1.05681	6.577	12.74	68.5	165	5	2.5	20	17.9	9	3.6	
mU233																		
zrhna23_a	10.05	10.5	22	91	11	22	1.0795	6.06	3.76	38.4	113	5	2.5	10	38	9	4.8	
zrhna23_b	10.05	10.5	22	75	10	20	1.5218	6.299	4.49	30	94.5	5	2.5	15	23.9	9	3.23	
zrhna23_c	10.05	10.5	22	75	10	20	1.0658	6.557	7.45	38	110	5	2.5	20	16.8	9	2.3	
mCm245																		
zrhna65_a	10.05	10.5	22	91	11	22	1.07532	6.06	0.431	38.4	112.6	5	2.5	10	348	9	15.1	
zrhna65_b	10.05	10.5	22	75	10	22	1.0894	6.852	0.914	32.5	97	5	2.5	25	116	9	6.2	
zrhna65_c	10.05	10.5	22	83	10.5	23	1.0779	8.288	2.297	45.4	115	5	2.5	45	47	9	2.9	

Table 3. List of major design parameters used to assess the effect of alternative fissile nuclides. Colored columns list the H/M fissile atom ratio and the total reactor subsystem mass. Shield and power conversion are not included.

Based on examination of Table 3 and Figure 4, a number of observations can be made.

1. Water cooled/moderated systems have lower mass estimates than all other reactor subsystems studied.
2. The type of fissile isotope (U-233 or Cm-245) strongly influences reactor subsystem mass estimates in gas and sodium-cooled reactors. U-233 or Cm-245 fuel reduces the reactor subsystem by almost a factor of two from a similarly designed gas or sodium cooled U-235 system.
3. The type of fissile fuel type within water cooled/moderated does not strongly affect the mass of the reactor subsystem.

4. For gas and sodium-cooled systems, higher H/M ratios generally increase the system mass (about 1.3 kg per increment in H/M ratio, e.g.; moving from an H/M ratio of 15-20 will increase the system mass by about 8 kg. ). In water systems within the range of H/M investigated there are no strong increases in system mass with increasing H/M ratio. These observations are just a reflection of the observation made earlier in Figure 1. The total system mass has a broad minimum near H/M ratios near 30.
5. Sodium cooled systems have lower mass estimates than do gas systems. This is occurred in these calculations because we assumed that the pitch could be reduced compared to a gas-cooled system because sodium is such a good coolant which allowed increasing the average density fissile isotope within the core.

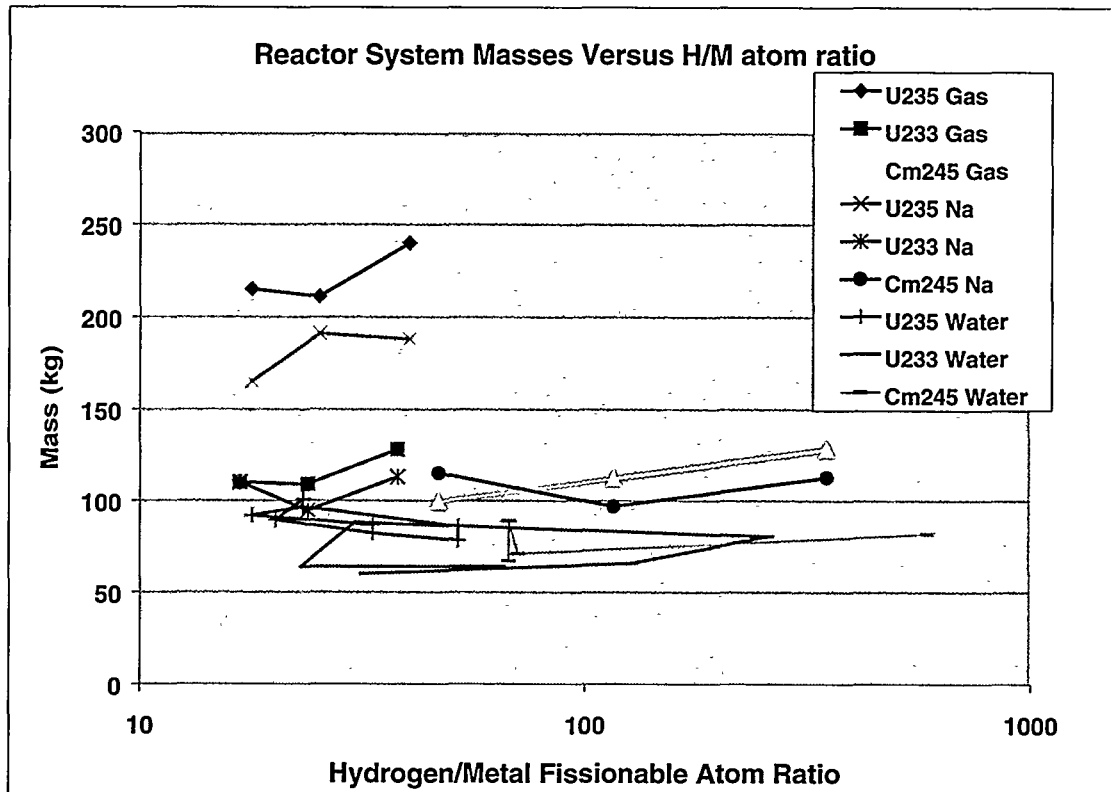


Figure 3. Graph of total reactor subsystem mass as a function of H/M fissile atom ratio.

## CONCLUSIONS

This report attempts to determine how small can nuclear reactor subsystems can be designed to and still be capable of operating at 60 kW thermal. It investigates the effect of Hydrogen to fissile metal atom ratio, water versus gas or sodium cooling, and alternative fissile isotopes. The result of this analysis indicate that very low mass systems can be identified and they have total reactor subsystem masses on the order of 60 for water cooled U-233 systems and 110 kg for gas or sodium cooled U-233 reactors. Low enrichment of Cm-245 available from spent fuel appears to offer no real advantage over U-233 reactor cores.

Water cooled UZrH fuel reactors that use steam Rankine power conversion systems should seriously be considered for use in space and planetary reactor applications because of the very low mass reactors that can be developed. Other advantages are that they operate at low temperature (~250 C), have high power conversion efficiencies, and have long life. Furthermore the fuel type is fully developed, commercially available, has been used in over 60 TRIGA research reactors, is well characterized, has unique safety features including prompt negative temperature coefficient of reactivity, and has high fission product retention. All of these features will tend to lower the cost and risk associated with developing a successful

space reactor. Still the use of water in weightless space or very cold planet surfaces (especially for power conversion) must be fully developed and tested.

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