

Analysis of the Proliferation Resistance of the  
Modular Pebble Bed High Temperature Gas Reactor

by

Jennifer Marie Anderson

Submitted to the Department of Nuclear Engineering in Partial  
Fulfillment of the Requirements for the Degree of

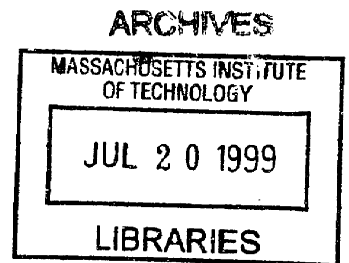
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ABSTRACT

The Modular Pebble Bed High Temperature Gas Reactor (MPBR) being designed by the Massachusetts Institute of Technology and the Idaho National Engineering and Environmental Laboratory operates with an online refueling system. This leads to an increased risk of proliferation because the fuel pebbles can be diverted while the plant is operating.

In order to show that the MPBR does not pose a proliferation risk the fuel content was determined for different burnups up to 94 MWD/kg. This data shows that the fuel is very poor nuclear weapon material. Safeguard systems were also designed in agreement with the International Atomic Energy Agency's standards to prevent diversion of significant quantities of fissile material.

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# TABLE OF CONTENTS

<b>1. INTRODUCTION .....</b>	<b>7</b>
1.1 Basic plant design .....	8
1.2 Pebble design .....	8
<b>2. WEAPONS MATERIAL .....</b>	<b>10</b>
2.1 Ideal fuel form for weapons.....	10
2.2 MPBR fuel composition.....	13
2.2.1 Uranium composition .....	13
2.2.2 Plutonium composition.....	14
2.2.3 Decay heat and spontaneous fission rates.....	16
2.3 Comparison to other fuel cycles .....	18
2.3.1 LWR with 4.5% enriched uranium fuel.....	19
2.3.2 LWR with 8% enriched uranium fuel.....	20
2.3.3 LWR with 19.5% enriched uranium fuel, 25% uranium-75% thorium.....	21
2.3.4 LWR with 19.5% enriched uranium fuel, 35% uranium-65% thorium.....	22
2.4 Chapter Summary .....	23
<b>3. FUEL HANDLING SYSTEM .....</b>	<b>24</b>
3.1 AVR fuel handling system.....	24
3.1.1 Diversion points .....	26
3.2 ESKOM refueling system.....	28
3.2.1 Normal operation.....	28
3.2.2 Defuelling Mode.....	30
3.2.3 Refueling Mode.....	31
3.2.4 Diversion points .....	31
3.3 Chapter Summary .....	32

<b>4. IAEA SAFEGUARDS.....</b>	<b>33</b>
<b>4.1 Definitions.....</b>	<b>33</b>
4.1.1 Significant quantities and timely detection.....	33
4.1.1.1 Uranium.....	34
4.1.1.2 Plutonium.....	35
4.1.2 Probabilities.....	35
<b>4.2 Considerations for implementation.....</b>	<b>36</b>
<b>4.3 Safeguard methods .....</b>	<b>36</b>
4.3.1 Nuclear material accountancy (NMA).....	36
4.3.2 Containment and surveillance (C/S).....	37
4.3.2.1 Locks and seals .....	37
4.3.2.2 Cameras .....	37
4.3.2.3 Inspections .....	38
<b>4.4 Safeguards for MPBR .....</b>	<b>38</b>
4.4.1 Areas of concern.....	38
4.4.1.1 New fuel storage .....	39
4.4.1.2 Scrap container.....	39
4.4.1.3 Used fuel storage tank .....	39
4.4.1.4 Spent fuel storage.....	40
4.4.1.5 Piping.....	40
4.4.2 Methods for MPBR .....	41
<b>4.5 Chapter Summary .....</b>	<b>42</b>
<b>5. CONCLUSION.....</b>	<b>43</b>

## Table of Figures

Figure 1: MPBR core cross section .....	9
Figure 2: TRISO fuel particle.....	9
Figure 3: Uranium Composition.....	14
Figure 4: Plutonium Composition.....	16
Figure 5: AVR fuel discharge wall.....	27
Figure 6: AVR fuel handling system overview .....	26
Figure 7: ESKOM fuel handling system.....	30
Table 1: Isotopic mixes of various plutonium grades .....	11
Table 2: Plutonium characteristics.....	12
Table 3: Uranium content of MPBR fuel .....	13
Table 4: Plutonium content of MPBR fuel.....	15
Table 5: Decay heat and spontaneous fission rate.....	17
Table 6: Predetonation probabilities .....	18
Table 7: Plutonium content for 4.5% enriched Uranium fuel in LWR.....	20
Table 8: Plutonium content for 8% enriched Uranium fuel in LWR.....	21
Table 9: Plutonium content for ThO <sub>2</sub> -25%UO <sub>2</sub> fuel in LWR ( <sup>235</sup> U enrichment 19.5%).....	22
Table 10: Plutonium content for ThO <sub>2</sub> -35%UO <sub>2</sub> fuel in LWR ( <sup>235</sup> U enrichment 19.5%).....	23
Table 11: Pebbles necessary for plutonium weapon .....	44
Table 12: Pebbles necessary for uranium weapon .....	44

# 1. Introduction

The Nuclear Engineering Department at the Massachusetts Institute of Technology (MIT) is working, in cooperation with Idaho National Engineering and Environmental Laboratory (INEEL), on the development of a Modular Pebble Bed High Temperature Gas Reactor (MPBR). The main goal for this project is to create a nuclear reactor that can compete economically with natural gas as a power generator.

Since the MPBR design is dependent on an online refueling system, the proliferation resistance of the plant is an important issue. It is essential to determine how much potential there is for a terrorist or a state to divert the fuel into a nuclear weapon program and to know what form the fuel will be in at the time of any possible diversion. The MPBR fuel becomes increasingly difficult to use for a weapon as the burnup increases. This is due to the changing plutonium isotopic concentrations that lead to increasing heat and a decreasing fissile content. Therefore the fuel is most attractive for use in a weapon following only one or two cycles through the core.

The International Atomic Energy Agency (IAEA) has standards it employs at all plants subject to their safeguards. In order to combat the problem of diversion it will be necessary to employ safeguards specific to the MPBR in the plant. These measures should help to both prevent diversion and provide for the timely detection of any diversion that does occur. The MPBR does not pose a proliferation risk when operated in a country that abides by the IAEA safeguards.

## **1.1 Basic plant design (Ref. 12)**

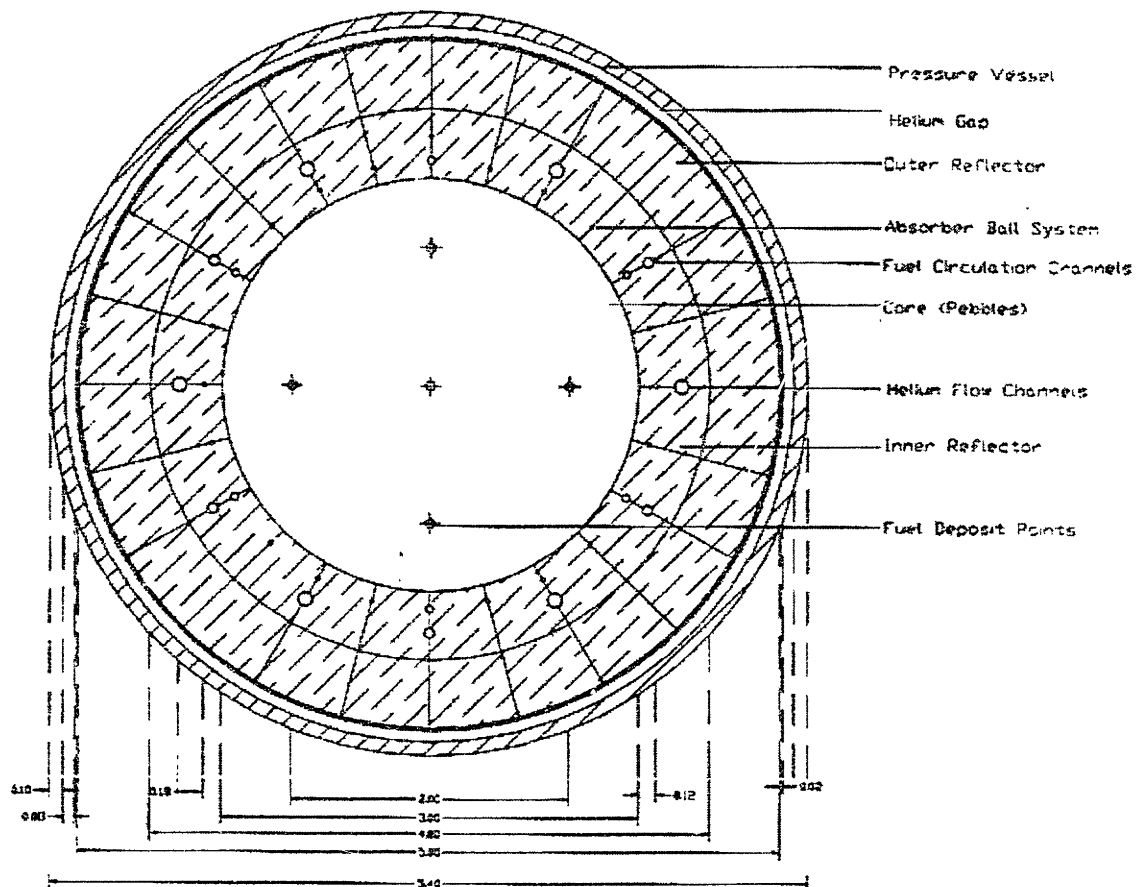
The MPBR plant utilizes a brayton power cycle. The plant consists of a core of fuel pebbles through which helium gas circulates. The helium travels to an intermediate heat exchanger where it deposits its heat in a secondary helium loop which then travels through the turbomachinery creating useable energy. The MPBR being designed by MIT has a thermal power output of 250 MW and an electric power of 116 MW. The core has a height of 10.0 meters and a diameter of 3.0 meters. The mean power density is 3.54 MW/m<sup>3</sup>. The center of the core contains fuel pebbles while the outside ring consists of graphite absorber balls which can be seen in Figure 1. There is no reprocessing necessary for the operation of the MPBR and the spent fuel can be directly disposed of in a spent fuel repository.

## **1.2 Pebble design (Ref. 12)**

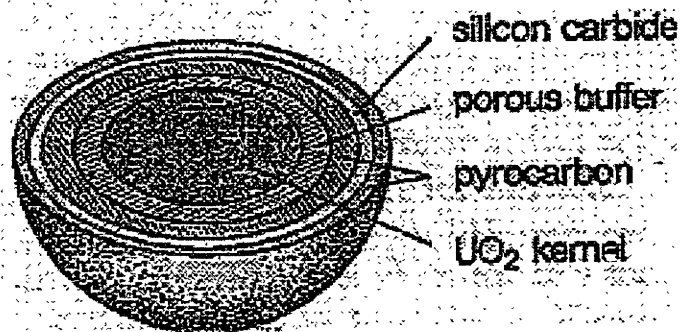
The core of the MPBR contains approximately 360,000 fuel pebbles, each around the size of a billiard ball. Each pebble contains approximately 11,000 low enriched uranium (LEU) microspheres that are embedded in a graphite matrix. With the matrix the pebble is 60 mm in diameter. The microspheres are enriched to 8%. They are TRISO type coated fuel particles that consist of layered coats of pyrocarbons and silicon carbide as shown in Figure 2. Each pebble contains approximately seven grams of LEU. It will cycle through the core roughly fifteen times before it is discharged into the spent fuel containers. This recycling leads to an opportunity for potential proliferators to divert the fuel at various burnup levels throughout the pebble's lifetime.



**Figure 1: MPBR core cross section**



**Figure 2: TRISO fuel particle**



## 2. Weapons material

In order to discuss the proliferation resistance of the plant it is necessary to know what will and will not make a good nuclear weapon in order to show that the MPBR fuel does not meet these specifications.

### 2.1 Ideal fuel form for weapons

There are three grades of plutonium that are routinely discussed: super-grade, weapons-grade, and reactor-grade. "Reactor-grade plutonium (RGPu) has a higher concentration of isotopes other than  $^{239}\text{Pu}$  than weapons-grade plutonium (WGPu). (Table 1) As a consequence of the higher alpha, gamma, and spontaneous neutron emissions of these isotopes, there are potential problems involved in using RGPu as a substitute for WGPu in weapons, e.g., the yield may be reduced, the shelf-life may be shorter, and the radiation exposure to workers during weapons fabrication may be greater. The difficulty in overcoming these problems and the need to do so depends on the type of weapon and its intended use, as well as the skill of the designer and the premium placed on worker health and safety.

For example, if RGPu were used in the Nagasaki bomb, there would have been a very high probability (99%) that the neutron chain reaction would be initiated prematurely because of the high neutron background due to spontaneous fission of the isotopes  $^{238}\text{Pu}$  and  $^{240}\text{Pu}$ . (Table 2) The result would be a significant reduction in the yield. While more sophisticated pure fission weapons developed after World War II are less sensitive to preinitiation, they do not eliminate it entirely. However, "boosted" fission weapons - where a low-yield fission explosion is used to fuse a mixture of

deuterium and tritium thereby generating high-energy (14 MeV) neutrons which greatly increase the fission yield - can be designed so as to be virtually immune to preinitiation.

The problems of the excess heat and radiation generated by RGPu can be managed by increasing the thermal conduction between the plutonium core and the outside of the weapon and by using additional shielding at warhead fabrication facilities, respectively.” (Ref. 11)

**Table 1: Isotopic mixes of various plutonium grades (Ref. 10)**

Grade	Isotope				
	<sup>238</sup> Pu	<sup>239</sup> Pu	<sup>240</sup> Pu	<sup>241</sup> Pu	<sup>242</sup> Pu
Super-grade	-	98.0%	2.0%	-	-
Weapons-grade	0.012%	93.8%	5.8%	0.35%	0.022%
Reactor-grade	1.3%	60.3%	24.3%	9.1%	5.0%

Spontaneous fission rate and decay heat are the important parameters to consider when choosing fissile material for a nuclear weapon. A high spontaneous fission rate could lead to detonation before the critical mass of the weapon is fully assembled. In the early stages of nuclear weapon development it was realized that this could significantly reduce the yield of the weapon. The decay heat is also an important parameter to consider from both a handling and a construction perspective. A large decay heat makes it more difficult to handle the fissile material during weapon assembly. Additionally if the decay heat is large enough it is possible that the fissile material could damage the chemical explosives used to compress the plutonium pit leading to either a reduced yield, or no yield at all. The spontaneous fission rate and decay heat are listed for the different plutonium isotopes in Table 2. <sup>238</sup>Pu has both a high spontaneous fission rate and a large

decay heat which makes it an effective poison for a weapon if it is present in a substantial quantity. Even a 5% <sup>238</sup>Pu content can significantly affect the ability to construct a reliable weapon.

The external radiation dose from both neutrons and gammas is also an important characteristic of weapon material. The gammas will be dominated by the <sup>241</sup>Pu decay chain. <sup>241</sup>Pu decays with a half-life of 14.4 years to <sup>241</sup>Am which then decays with a half-life of 430 years. (Ref. 11)

**Table 2: Plutonium characteristics (Ref. 10)**

Isotope	Half-life <i>Years</i>	Bare Critical Mass <i>Kg, α-phase</i>	Spontaneous fission neutrons <i>Neutrons/sec-kg</i>	Decay heat <i>Watts kg<sup>-1</sup></i>
<sup>238</sup> Pu	87.7	10	2.6 • 10 <sup>6</sup>	560
<sup>239</sup> Pu	24,100	10	22	1.9
<sup>240</sup> Pu	6,560	40	9.1 • 10 <sup>5</sup>	6.8
<sup>241</sup> Pu	14.4	10	49	4.2
<sup>242</sup> Pu	376, 000	100	1.7 • 10 <sup>6</sup>	0.1

<sup>238</sup>Pu content increases with burnup levels while <sup>239</sup>Pu content decreases. Thus if the fuel is taken to a higher burnup it presents less of a proliferation risk. This fact has led to new reactors being designed to go to higher burnup levels. The MPBR is being designed to go to a burnup of 80,000 to 100,000 MWD/MT. Since the pebbles will cycle through the core numerous times it is important to determine the fuel composition at various points in the pebble's lifetime in order to assess its proliferation resistance.

## 2.2 MPBR fuel composition

Dr. Thomas Cochran of the Natural Resources Defense Council (NRDC) ran a code (Ref. 4) that calculated the isotopic concentration of the MPBR fuel at multiples of 10 MWD/kg up to 90 MWD/kg and including 94 MWD/kg which was the highest burnup the code would allow. The calculations were done for a high power gas-cooled reactor with a specific power of 100 kW/kg. This was determined using a diameter of 3.0 meters, a height of 10.0 meters, and a mean power density of 3.54 MW/m<sup>3</sup> for the MPBR core. The original fuel input used was one metric ton of uranium enriched to 8% <sup>235</sup>U.

### 2.2.1 Uranium composition

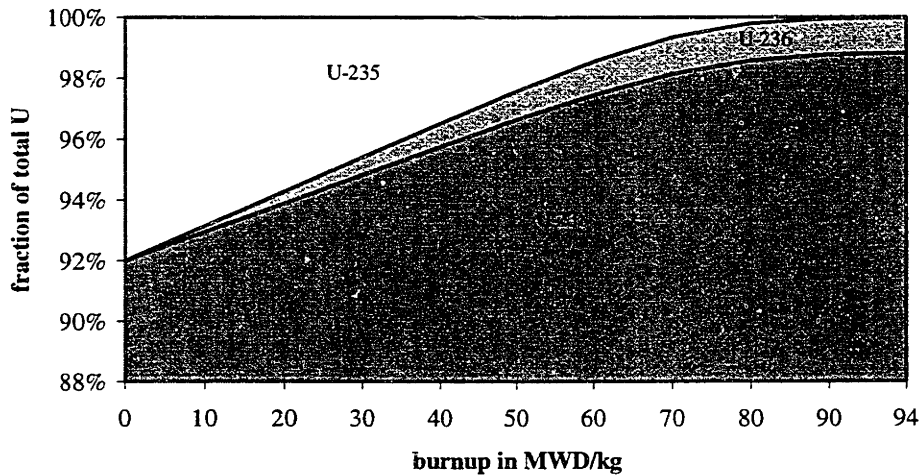
**Table 3: Uranium content of MPBR fuel (Ref. 4)**

Isotope	Burnup (MWD/kg)										
	0	10	20	30	40	50	60	70	80	90	94
U-235	8.00%	6.85%	5.71%	4.58%	3.47%	2.41%	1.44%	0.66%	0.19%	0.04%	0.02%
U-236	0.00%	0.20%	0.40%	0.59%	0.78%	0.95%	1.10%	1.20%	1.22%	1.17%	1.14%
U-238	92.00%	92.95%	93.89%	94.83%	95.75%	96.64%	97.46%	98.15%	98.59%	98.80%	98.84%
kg U/ton	1000.0	988.7	977.6	966.5	955.4	944.3	933.1	921.8	910.4	899.1	894.8

Table 3 contains the uranium isotopic concentrations at 10MWD/kg intervals. The percentages listed in this table, as well as the rest of the tables in this paper, are weight percent. Also the masses listed are per metric ton of initial heavy metal (ihm). The concentrations of all but <sup>235</sup>U, <sup>236</sup>U and <sup>238</sup>U are inconsequential and thus are not shown. The <sup>235</sup>U almost disappears at 90.MWD/kg and the fuel is left with just <sup>238</sup>U and a small amount of <sup>236</sup>U. The relation between the different isotopes is shown clearly in

Figure 3. The total mass of uranium at 94 MWD/kg is 894.8 kg, 99.2% of the total fuel mass. This shows that the discharged fuel will remain mostly  $^{238}\text{U}$ .

**Figure 3: Uranium Composition**



### 2.2.2 Plutonium composition

The plutonium content of the fuel was also determined by the code (Ref. 4). After a burnup of 94 MWD/kg one metric ton of fuel produced 6.296 kg of plutonium which is less than 1% of the total mass remaining. Additionally it is important to consider that the core consists of approximately 2.5 metric tons of uranium when it is fully loaded. Thus it is necessary to divert at least half of the core in order to obtain enough plutonium to manufacture a weapon. This plutonium, as can be seen in Figure 4, is not ideal weapons material due to the relatively high  $^{238}\text{Pu}$  content and the low  $^{239}\text{Pu}$  content. If a better isotopic mix is sought it will be necessary to divert an even larger percentage of the core. Table 4 shows that the plutonium mix is more favorable for weapons earlier in the burnup profile. The data at 0 MWD/kg reflects the fact that the first plutonium produced will be  $^{239}\text{Pu}$ . The  $^{239}\text{Pu}$  concentration drops over 9% for every

10 MWD/kg increase in burnup until 40-50 MWD/kg where it begins to level out a little.

When taking into account the mass (instead of the concentration) the gain per 10

MWD/kg begins to drop after 20 MWD/kg. Thus if the intention was to use the fuel for a

weapon it would be most advantageous to divert the fuel early in the cycle. However if

the fuel is diverted at a burnup around 20 MWD/kg more than two cores would be needed

to make a nuclear weapon. In order to manufacture a nuclear weapon from fully spent

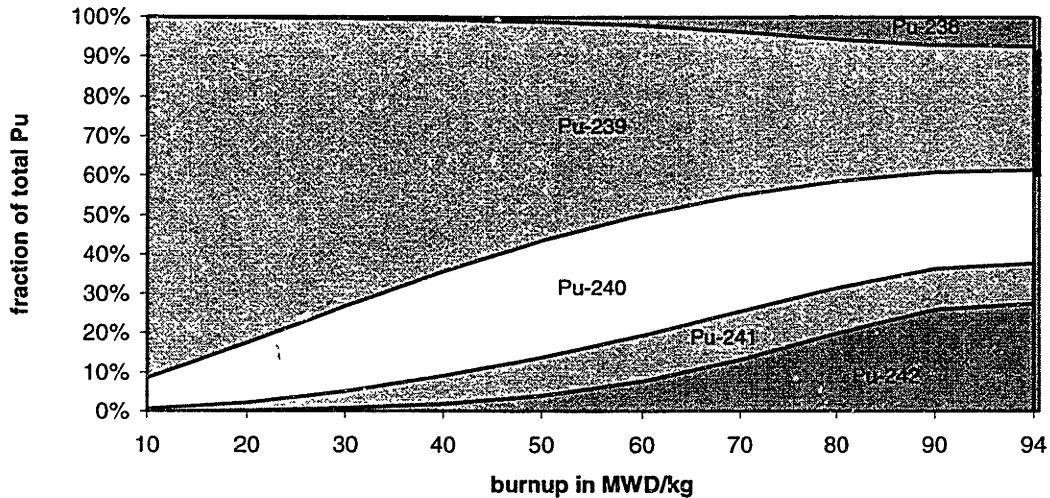
MPBR fuel half the core would be needed for an unreliable and difficult to handle

weapon.

**Table 4: Plutonium content of MPBR fuel (Ref. 4)**

Isotope	Burnup (MWD/kg)										
	0	10	20	30	40	50	60	70	80	90	94
Pu-238	0.0%	0.02%	0.10%	0.28%	0.60%	1.17%	2.14%	3.66%	5.58%	7.00%	7.28%
Pu-239	100%	91.49%	82.34%	72.96%	63.82%	55.32%	47.77%	41.28%	35.97%	32.19%	31.17%
Pu-240	0.0%	7.91%	15.23%	21.56%	26.48%	29.62%	30.70%	29.59%	26.93%	24.38%	23.67%
Pu-241	0.0%	0.56%	2.13%	4.47%	7.19%	9.80%	11.67%	12.24%	11.53%	10.52%	10.22%
Pu-242	0.0%	0.02%	0.20%	0.73%	1.90%	4.08%	7.73%	13.23%	19.98%	25.98%	27.66%
kg Pu/ton	0.0	0.8036	1.507	2.147	2.753	3.349	3.965	4.640	5.391	6.886	6.296

**Figure 4: Plutonium Composition**



### 2.2.3 Decay heat and spontaneous fission rates

The high concentration of the even numbered isotopes of plutonium leads to both a high decay heat and a high spontaneous fission rate. The decay heat and spontaneous fission rate listed in Table 2 for each plutonium isotope were used to compute the values listed for the three grades at a burnup of 94 MWD/kg in Table 5. The MPBR fuel at the end of life is twenty times warmer than weapons grade material. This will make the spent fuel difficult to handle.

A temperature was also calculated for a 6.1 kg mass of plutonium, this is the approximate mass of the trinity pit (the first nuclear weapon ever tested). It was assumed that the plutonium was in an 88 mm diameter sphere and that all the heat removal was by black body radiation with an emissivity of 1.0. This calculation approximates the surface temperature of the sphere if it was set on a table. The calculated sphere temperature of



397 °C (746°F) is above the flash point of wood (approximately 500 °F). Another factor to consider is that the melting temperature of high explosives used in weapon construction is around 200 °C. A more extensive thermal analysis would need to be done to determine the exact temperature of the fuel when surrounded by the explosive, but it is easy to see that thermal management of the weapon materials will be a nontrivial task.

**Table 5: Decay heat and spontaneous fission rate (Ref. 7)**

	Super grade	Weapons grade	MPBR
<b>Composition</b>			
Pu-238	0.0%	0.012%	7%
Pu-239	98.0%	93.80%	31%
Pu-240	2.0%	5.80%	24%
Pu-241	0.0%	0.35%	10%
Pu-242	0.0%	0.022%	28%
<b>Spontaneous Neutron Production</b>			
(n/kg-s)	1.82E+04	5.35E+04	8.75E+05
Relative	1.0	2.9	48.0
<b>Decay Heat</b>			
(W/kg)	2.0	2.3	43.4
Relative	1.0	1.1	21.7
<b>For a 6.1 kg sphere</b>			
<b>Spontaneous Neutrons</b>			
n/s	1.11E+05	3.26E+05	5.34E+06
<b>Decay Heat</b>			
W	12	14	265
<b>Temperature (C)</b>			
(F)	88	94	397
	190	201	746

The high spontaneous neutron production is also going to increase the difficulty of making a weapon out of the spent MPBR fuel. The presence of a strong spontaneous neutron source in the weapon material causes the pit to start a chain reaction before it is

completely compressed. This leads to a lower yield weapon. Table 6 shows the probability of a weapon reaching a certain percentage of its design yield. The spontaneous fission rate is so high in the MPBR fuel that there is less than a 50% chance of the weapon even reaching 4% of its design yield. It can be argued that any weapon is a good weapon however, the reliability of the MPBR fuel is so low potential proliferators will most likely look elsewhere for their fission source.

**Table 6: Predetonation probabilities (Ref. 7)**

Probability of exceeding x% of design yield	Super grade	Weapons grade	MPBR
4%	98.51%	95.70%	48.70%
5%	97.49%	92.81%	29.52%
6%	96.55%	90.19%	18.49%
8%	94.82%	85.55%	7.79%
10%	93.27%	81.49%	3.52%
15%	89.86%	73.07%	0.59%
20%	86.93%	66.29%	0.12%
25%	84.32%	60.61%	0.03%
50%	74.08%	41.44%	0.00%
99%	60.53%	22.90%	0.00%

### 2.3 Comparison to other fuel cycles

In order to get a better grasp on the isotopic mix comparisons can be made to fuel from other cycles. Tables 7-10 show the plutonium data for four different fuel cycles in a Light Water Reactor (LWR). All four fuels were irradiated at a power of 37.935 kW<sub>t</sub>/kg ihm. (Ref. 6) The first two fuels are uranium enriched to 4.5% and 8% <sup>235</sup>U. The 4.5% enriched fuel is only taken to a burnup of 45 MWD/kg (Table 7) while the 8% enriched fuel is taken to 72 MWD/kg (Table 8). The other two fuels are a mix of 19.5% enriched

uranium and thorium. The data in Table 9 is for 25% uranium (75% thorium) fuel that is burned to 72 MWD/kg. Table 10 is for 35% uranium (65% thorium) fuel taken to a burnup of 100 MWD/kg. It is important to note that a mixed thorium and uranium fuel can also be used in an MPBR. The 300 MW<sub>t</sub> Thorium High Temperature Reactor (THTR-300) in Germany as well as the Fort St. Vrain reactor in the United States have operated using this technology.

Comparisons between the final discharged fuel and for other points in the fuel lifetime where the burnup data points match show that the MPBR fuel is more proliferation resistant than both pure uranium fuels, but less resistant to proliferation than the mixed uranium and thorium fuels. This data shows that the MPBR is better than existing LWR reactors even though it may not be as proliferation resistant as mixed thorium and uranium fuels.

### **2.3.1 LWR with 4.5% enriched uranium fuel**

The isotopic mix of the 4.5% enriched uranium at 30 MWD/kg is more proliferation resistant than the MPBR at the same burnup (see Table 4). The LWR fuel has both a higher <sup>238</sup>Pu content and a lower <sup>239</sup>Pu. However the LWR produces four times the mass of plutonium in reaching 30 MWD/kg. If the final fuel forms of both cycles are compared, the MPBR fuel has a much better isotopic mix. Additionally the MPBR produces roughly five kilograms per metric ton less plutonium, so not only would the fuel be poor weapon material, but also a larger quantity would need to be diverted. The LWR fuel is also easier to handle because the decay heat is 16.1 W/kg (Ref. 7), less than half of that for the MPBR (see Table 5).

**Table 7: Plutonium content for 4.5% enriched Uranium fuel in LWR (Ref. 6)**

Isotope	Burnup (MWD/kg)			
	0	15	30	45
Pu 238	0.0%	0.3%	1.1%	2.3%
Pu 239	100.0%	78.1%	65.1%	55.8%
Pu 240	0.0%	13.4%	18.2%	21.2%
Pu 241	0.0%	7.4%	12.7%	14.9%
Pu 242	0.0%	0.7%	2.9%	5.8%
kg Pu/ton	0.000	5.889	9.564	11.890

### 2.3.2 LWR with 8% enriched uranium fuel

The 8% enriched uranium fuel comparison is not as straightforward. The LWR fuel has a higher  $^{238}\text{Pu}$  content at 60 MWD/kg, but it also has an almost 12% higher  $^{239}\text{Pu}$  content (see Table 4). This negates the advantages of the high  $^{238}\text{Pu}$  content. The LWR also produces over twice the amount of plutonium per metric ton ihm. By the end of life the MPBR will have a substantially higher  $^{238}\text{Pu}$  content, a substantially lower  $^{239}\text{Pu}$  content and close to ten kilograms per metric ton ihm less plutonium. The decay heat for the LWR is also just three-quarters (13.9 W/kg, Ref. 6) of the decay heat for the MPBR (see Table 5). Thus fuel of the same enrichment will be more proliferation resistant if used in a MPBR than in a LWR if you consider the higher burnup of the MPBR.

**Table 8: Plutonium content for 8% enriched Uranium fuel in LWR (Ref. 6)**

Isotope	Burnup (MWD/kg)						
	0	12	24	36	48	60	72
Pu 238	0.0%	0.2%	0.6%	1.2%	2.0%	3.1%	4.4%
Pu 239	100.0%	88.2%	78.9%	71.4%	65.1%	59.5%	54.6%
Pu 240	0.0%	7.8%	11.9%	14.6%	16.7%	18.4%	19.6%
Pu 241	0.0%	3.7%	7.8%	11.1%	13.3%	14.7%	15.4%
Pu 242	0.0%	0.2%	0.7%	1.7%	2.9%	4.3%	5.9%
kg Pu/ton	0.0	5.131	8.539	11.165	13.269	14.865	16.101

### 2.3.3 LWR with 19.5% enriched uranium fuel, 25% uranium-75% thorium

The mixed thorium and uranium fuel is much better for proliferation resistance than the standard uranium LWR fuel. It also compares favorably to standard uranium fuel in an MPBR fuel. The mixed fuel has a  $^{238}\text{Pu}$  content at 60 MWD/kg that is nearly four times that of the MPBR at the same burnup. Additionally the  $^{239}\text{Pu}$  content is 4% lower (Table 4). The mass of plutonium of the two only differs by 0.2 kg per ton. The mixed fuel is also better at the end of life where it still has a higher  $^{238}\text{Pu}$  content, and it produces two kilograms less plutonium. The MPBR fuel does have a 7% lower  $^{239}\text{Pu}$  content, but the mass and the  $^{238}\text{Pu}$  outweigh this. The decay heat for the thorium fuel is also substantially higher (63.4 W/kg, Ref. 6) than that of the MPBR (43.4 W/kg).

**Table 9: Plutonium content for ThO<sub>2</sub>-25% UO<sub>2</sub> fuel in LWR (<sup>235</sup>U enrichment 19.5%) (Ref. 6)**

Isotope	Burnup (MWD/kg)						
	0	12	24	36	48	60	72
Pu 238	0.0%	0.4%	1.5%	3.3%	5.7%	8.3%	10.8%
Pu 239	100.0%	81.1%	67.5%	57.3%	49.5%	43.5%	38.9%
Pu 240	0.0%	11.8%	16.1%	18.3%	19.4%	19.8%	19.8%
Pu 241	0.0%	6.2%	12.6%	16.0%	16.8%	16.1%	14.9%
Pu 242	0.0%	0.5%	2.3%	5.1%	8.6%	12.2%	15.6%
kg Pu/ton	0.0	1.9723	3.07298	3.6725	3.9905	4.1506	4.2548

### 2.3.4 LWR with 19.5% enriched uranium fuel, 35% uranium-65% thorium

A larger quantity of plutonium is produced in the 65% thorium fuel due to the higher uranium content (see Table 4). At 50 MWD/kg there is nearly four times more <sup>238</sup>Pu in the LWR, but there is only a 1% difference in <sup>239</sup>Pu between the MPBR and LWR. The LWR does produce two kilograms more plutonium, a 60% increase. At the end of the cycle the LWR has almost twice the <sup>238</sup>Pu content in addition to an equal mass of plutonium. The MPBR has 5% less <sup>239</sup>Pu, but in light of the nearly 14% <sup>238</sup>Pu content the 5% difference in <sup>239</sup>Pu is insignificant. Additionally the thorium fuel is nearly twice as hot (80.7 W/kg, Ref. 6) as the MPBR fuel (43.4 W/kg).

**Table 10: Plutonium content for ThO<sub>2</sub>-35% UO<sub>2</sub> fuel in LWR (<sup>235</sup>U enrichment 19.5%) (Ref. 6)**

Isotope	Burnup (MWD/kg)				
	0	25	50	75	100
Pu 238	0.0%	1.14%	4.42%	9.37%	13.94%
Pu 239	100.0%	73.59%	56.34%	44.33%	36.40%
Pu 240	0.0%	13.87%	17.89%	19.24%	19.44%
Pu 241	0.0%	10.09%	15.98%	16.16%	13.95%
Pu 242	0.0%	1.31%	5.38%	10.90%	16.26%
kg Pu/ton	0.0	3.874	5.489	6.070	6.247

## 2.4 Chapter Summary

The usefulness of reactor-grade plutonium for weapon production is dependent on the mixture of plutonium isotopes. The even number isotopes, particularly <sup>238</sup>Pu, have high decay heats and spontaneous fission rates (see Table 2). If the relative quantities of these isotopes are high enough they can make building a weapon extremely difficult if not impossible. Thus increasing the content of the even numbered plutonium isotopes in spent fuel is a condition for increasing the proliferation resistance of the particular fuel.

The MPBR fuel is particularly unattractive to potential proliferators at the end of life due to the poor plutonium isotopic mix, the low quantity of plutonium produced, the high decay heat, and the high spontaneous fission rate. While slightly more attractive at lower burnups, the fuel is still less attractive for building weapons than that found in a standard LWR. The thorium fuels provide added proliferation resistance due to their high percentage of <sup>238</sup>Pu and thus their extremely high decay heat. If additional proliferation resistance is required, the MPBR could be operated on a thorium fuel cycle.

### 3. Fuel handling system

The fuel handling system has not been specifically designed by MIT at this point. However, since Germany has operated their AVR, an experimental high-temperature reactor, and ESKOM (in South Africa) has begun construction on a pebblebed reactor, their systems are available to base possible designs on. The fuel handling system that MIT uses will look like ESKOM's system.

#### 3.1 AVR fuel handling system (Ref. 1)

The basic design of the AVR fuel handling system is very simple. It is illustrated in Figure 5. The pebbles are initially placed in a fueling room from which they enter the fuel system when new pebbles are needed due to the discharge of others. After traveling through the core from top to bottom the pebbles are funneled into the reducer which is the first part of the fuel discharge wall that is illustrated in Figure 6. The reducer is a rotating disc with a slot that will allow a few pebbles to drop through each time it rotates. Following the reducer the pebble will go through the singulizer, a valve, and the failed fuel separator. The singulizer separates the pebbles into a single steady stream. The failed fuel separator separates damaged pebbles from the flawless ones. It then sends the damaged ones through another valve into the scrap can. The intact pebbles are sent to the dosing wheel where they are sent through different pipes back to the core depending on the burnup level. Pebbles that are entirely spent are sent through the discharge line and a series of valves to the discharge compartment. This whole system is automated. The AVR has a 15 MW<sub>e</sub> core of only 100,000 pebbles so the number recirculating through the



MIT core each day will be larger than the approximately 500 pebbles that pass through the AVR system daily.

### **3.1.1 Diversion points**

Some points in this system are inaccessible and others are highly accessible. Both the refueling room and the spent fuel room are easy to access, but they are both also easy to monitor. The pebbles can also be accessed in the failed fuel separator, the dosing wheel, and the scrap container because closing valves can isolate these items. The rest of the system is relatively inaccessible because there are no isolation valves and getting into the system would require cutting pipes or breaking welds. Additionally the possibility of detection is much greater when pipes are broken or systems are breached because this will usually cause the reactor to shutdown.

Figure 5: AVR fuel handling system overview

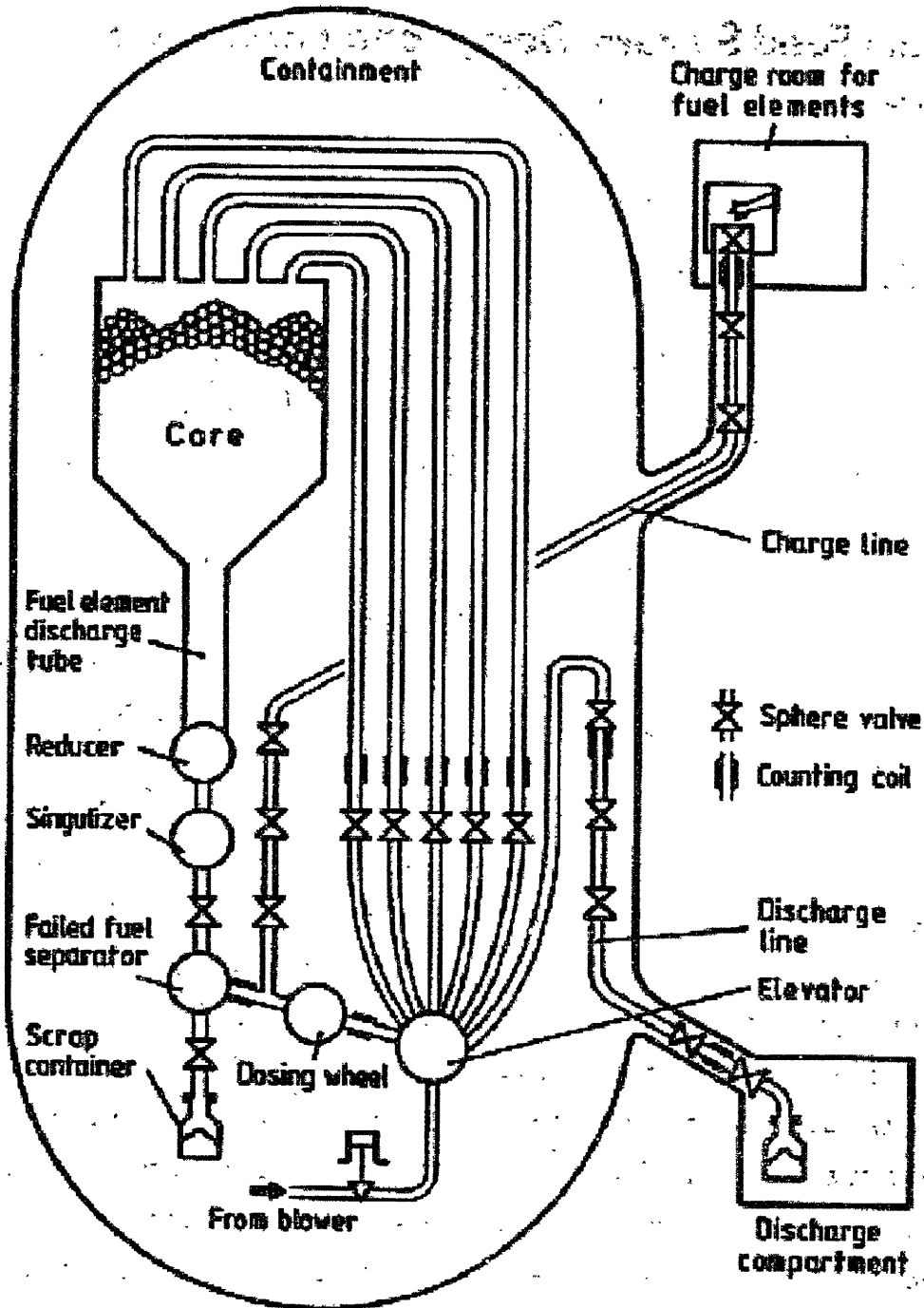
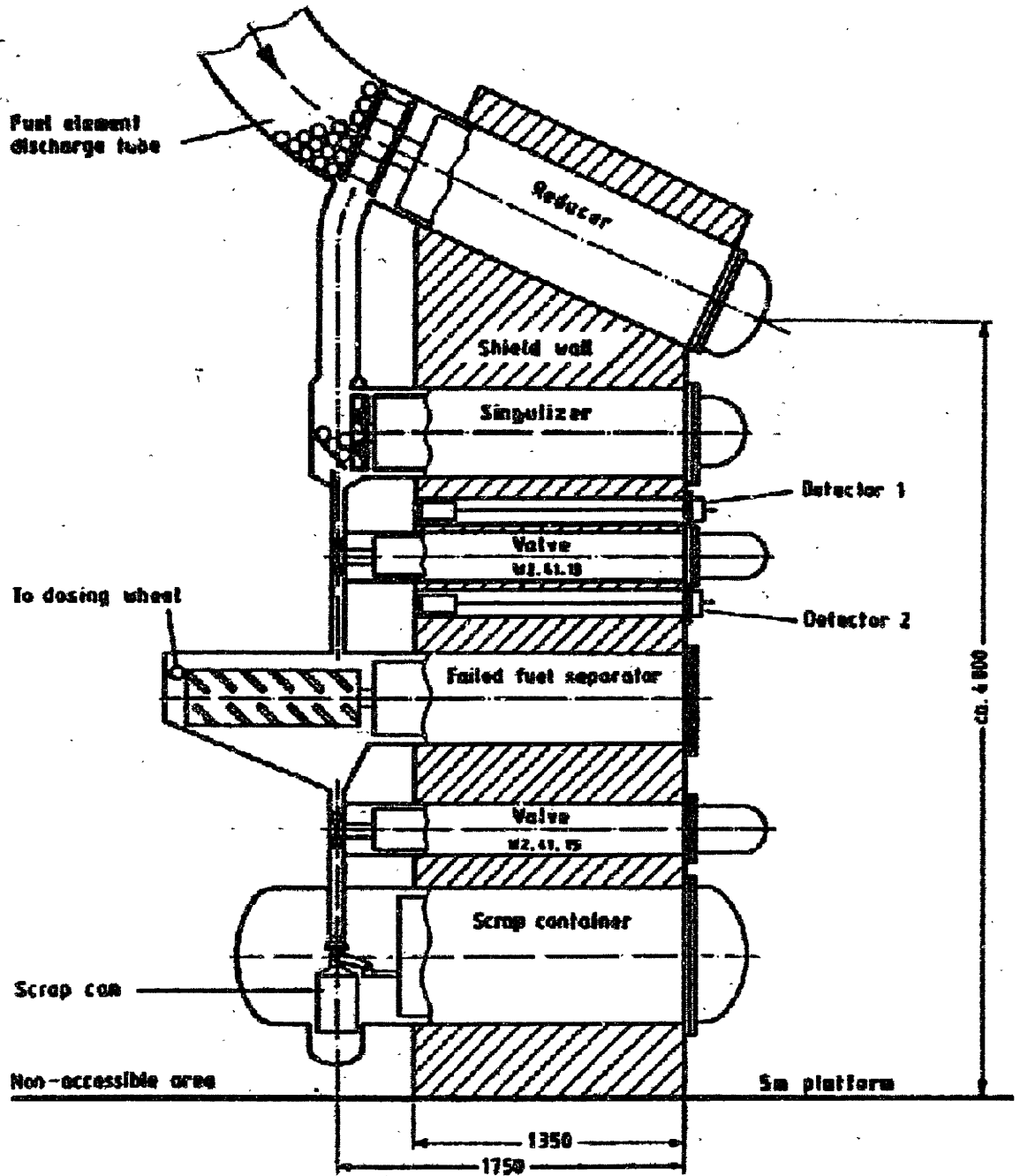


Figure 6: AVR fuel discharge wall



### **3.2 ESKOM refueling system (Ref. 5)**

The ESKOM refueling system is significantly different from the AVR due to the use of graphite pebbles within the ESKOM core. The graphite pebbles are used as central reflector in the center of the core and are surrounded by the fuel pebbles. This creates the need to sort the pebbles when they leave the core. Therefore some additional machinery and piping is necessary for not only the sorting, but also for a system to detect the different types of pebbles. Figure 7 shows the entire fuel handling system for both the graphite and the fuel pebbles. The ESKOM reactor produces 114 MW<sub>e</sub> as compared to MIT's 116 MW<sub>e</sub>. The ESKOM core contains approximately 331,000 fuel pebbles (92% of the MIT core) and 110,000 graphite pebbles.

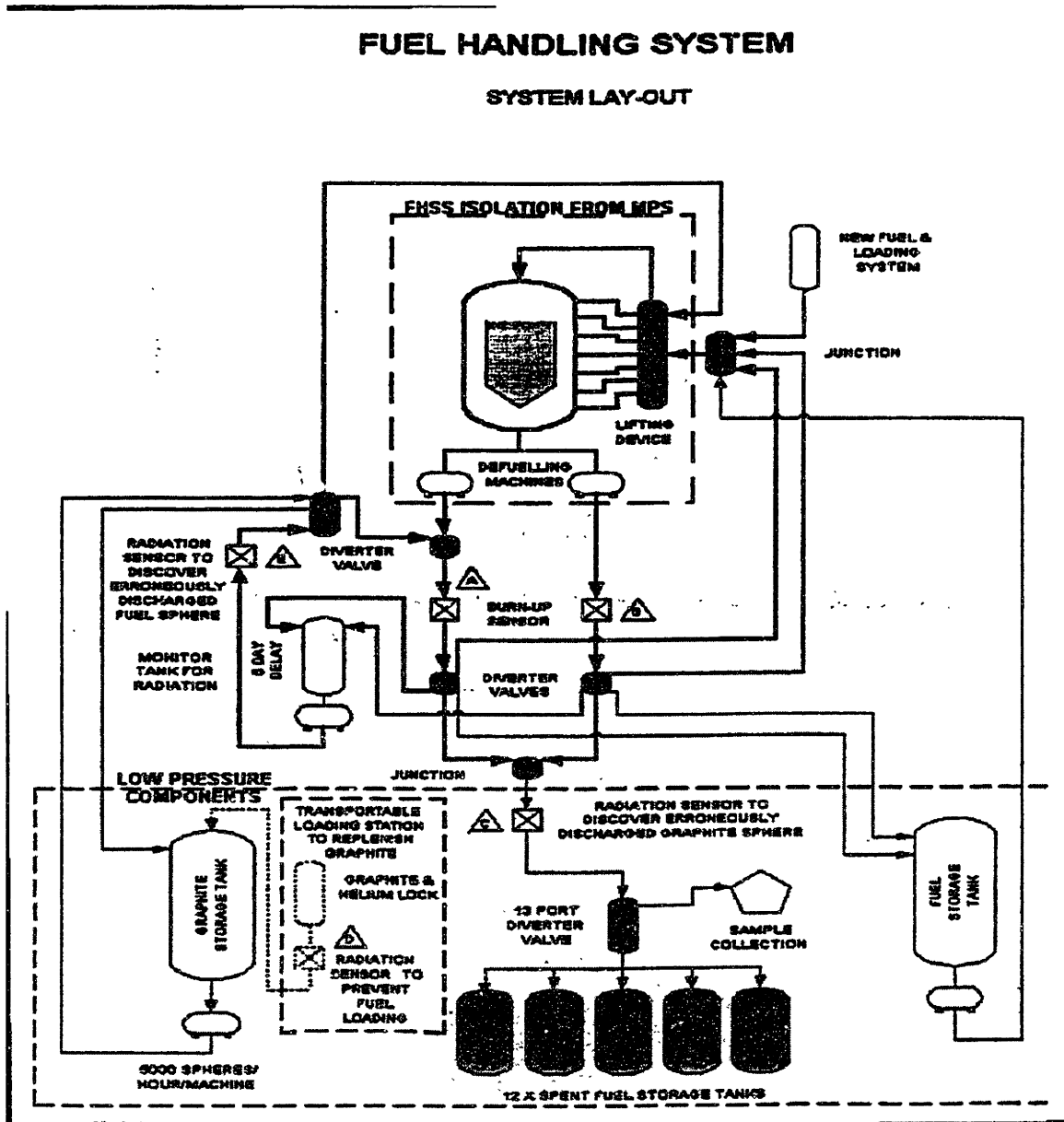
#### **3.2.1 Normal operation**

The fuel and graphite pebbles are loaded from separate tanks. It should not be necessary to replenish the store of graphite pebbles during the plant's lifetime since they can be recirculated indefinitely. However there is a component that provides for restocking the graphite in case it is necessary. The fuel is contained in double-walled hoop drums that hold approximately 1000 pebbles each. The new fuel room can hold 70 casks, which corresponds to a six-month supply of fuel. The cask must be unloaded by special semi-automatic machinery. To do this the shipping cask is tipped and the pebbles are removed one-by-one through a single-exit gate. The pebbles travel through a buffer pipe and then are sent into the system one-by-one through a rotary feed valve. Following this the fuel pebbles proceed directly to the core.

Once the pebbles have traveled through the entire core they are funneled out through the defueling machines. Damaged pebbles are sent to a scrap can (not shown on the diagram) and the rest of the pebbles are sent through a junction to a burnup sensor. The sensor determines whether or not the pebble is fuel or graphite, and what the burnup level is if it is fuel. The pebble then travels to a diverter valve which sends the graphite pebbles to the graphite buffer tank, the spent pebbles to spent fuel storage, and the still usable pebbles back to the core. The graphite pebbles sit in a buffer tank, which is monitored for radiation, for five days. After the five days the pebbles go through a radiation sensor to insure that all the pebbles are actually graphite. All the pebbles then go through another diverter valve where the graphite pebbles are sent back to the core. If any sorting mistakes were made and a fuel pebble was placed with the graphite, the fuel pebble will be sent back to the junction at the bottom of the tank. It will then travel back through the burnup sensors and will be diverted to the correct pipe.

The fuel pebbles that are still usable are sent directly back to the core. The spent fuel is sent through a junction to another radiation sensor to make sure the pebble isn't graphite. As each pebble passes through the radiation sensor a new fuel pebble is brought into the system. However, if a graphite sphere is detected a new fuel sphere will not be loaded. Unlike an erroneously placed fuel pebble, a graphite pebble that is placed in the spent fuel system can not be returned to the graphite system. After the radiation sensor the pebbles travel through a diverter valve which places the pebbles in one of twelve spent fuel storage tanks or in the sample collection tank. The sample tank can be used to check to make sure the pebbles going to spent fuel storage have reached peak burnup.

Figure 7: ESKOM fuel handling system



### 3.2.2 Defueling Mode

It may be necessary to remove all the fuel from the core at times. In this case instead of the fuel pebbles traveling to either the core or spent fuel storage they go to the fuel storage tank that will initially be empty. There is nothing to physically separate the graphite pebbles in the center of the core from the fuel pebbles around them in the ESKOM reactor. Therefore during defueling it is necessary to separate the graphite

pebbles and return them to the outside of the core where the fuel pebbles had been to prevent the shifting of the graphite center. While the core is in defueling mode no new fuel can be added and no graphite pebbles can be loaded into the graphite storage tank.

### **3.2.3 Refueling Mode**

Following defueling the core is reloading from the fuel storage tank. The graphite pebbles will be removed from the core at the same rate the fuel is added. After being redirected to the graphite handling system the graphite pebbles will first fill the buffer storage tank, once this tank is full the graphite pebbles will be sent back to the graphite storage tank.

### **3.2.4 Diversion points**

There are four possible diversion points which would allow access to a large number of pebbles at one time in the ESKOM fuel handling system: the new fuel loading room, the scrap fuel container, the spent fuel storage container, and the defueling storage tank. Fuel could also be accessed at the burnup and radiation sensors because they can be isolated by valves. Access at other points would require cutting pipes or breaking welds, as in the AVR. Each spent fuel storage tank weighs 12 metric tons when empty and 80 metric tons when full. Thus picking one of them up is not an option. As in the AVR monitoring the new fuel casks would not be a difficult endeavor. The fuel storage tank is only used when the core is being defueled which makes it an unlikely point for diversion. Therefore the most opportune point for diversion would be the scrap container.

### **3.3 Chapter Summary**

The refueling system for both the AVR and the ESKOM reactor are very similar. The pebbles are circulated through the core and then pass through radiation detectors. The detectors determine the pebble's next destination based on burnup. The pebble then travels through the piping system either back to the scrap container, to the core or to the spent fuel containers. The pebbles sent to the core repeat the loop, the pebbles that are removed from the system are replaced by fresh fuel.

The most likely diversion points are the locations where the most fuel is located. First, fresh fuel storage contains 70 movable casks of 1000 fresh pebbles when full. Second, spent fuel storage will contain an increasing number of pebbles, however the casks are built into the facility and weigh 12 metric tons when empty. Third, the scrap container could be accessed but will contain an extremely small amount of fuel compared to the other locations. And finally, the fuel storage tank used during defueling will contain a full core of pebbles.



## **4. IAEA safeguards**

The International Atomic Energy Agency (IAEA) is responsible for enforcing the Nuclear Non-Proliferation Treaty (NPT). The states that have signed this treaty have pledged to not develop nuclear weapons if they do not already possess them. In order to prove that they are keeping their word the nuclear facilities in the state are expected to abide by IAEA safeguards. The IAEA has a technical objective of “the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown and deterrence of such diversion by risk of early detection”. (Ref. 8)

Essentially the IAEA tries to prevent diversion of nuclear material by both technical means and the threat of being discovered. The IAEA accomplishes this objective in many ways including inspections, locks, seals, and electronic monitoring such as cameras.

### **4.1 Definitions**

#### **4.1.1 Significant quantities and timely detection (Ref. 8)**

The definition of a significant quantity and a timely detection differ depending on the material being discussed, either uranium or plutonium. A significant quantity refers to an approximate amount of material that would be necessary if it were being used to make a nuclear weapon. The definition of timely detection considers the time necessary to convert the diverted material into a form that could be used for the nuclear weapon.

#### 4.1.1.1 Uranium

A significant quantity of uranium is defined as 25 kg of  $^{235}\text{U}$ . If the reactor is using LEU fuel this increases to 75 kg. For the MPBR 75 kg of  $^{235}\text{U}$  translates into nearly 134,000 pebbles, or over 37% of our core. If you translate this into the ESKOM fuel shipping containers it would equal 134 casks, nearly twice the number stored at the plant in the new fuel room. In addition to the large number of pebbles necessary, it is extremely difficult to make a weapon with a uranium enrichment less than 20%. The critical mass of uranium enriched to 10% is approximately 750 kg. This shows that in order for the unburned MPBR fuel to be used for a weapon significant enrichment would need to take place. Since the fuel pebbles would be supplied to any country the MPBR is exported to, only countries that possess a clandestine enrichment facility would be able to use the unburned pebbles for nuclear weapons. Additionally all the calculations of the number of pebbles necessary assume that it will be possible to extract all the uranium from the pebble. This process involves burning the graphite matrix and chemically separating the fissile material. While it should be assumed that anyone who has possession of the pebbles could perform this process, it is difficult to be 100% efficient and remove all of the fissile material. This will lead to a small increase in the number of pebbles actually needed to construct a weapon.

Timely detection in the case of uranium is considered a year. This is considered the minimum amount of time that it will take to reprocess the fuel into a weapon-usable form. It is difficult to imagine 134 casks of fuel disappearing in a year without it being noticed since this is approximately a full year's supply of fuel. Even if individual pebbles

were stolen it would be at a rate of 367 pebbles a day for an entire year. This would definitely require more than one person to take pebbles each day. The chances of this diversion not being noticed by the cameras and other minimal security in the plant are very slim.

#### **4.1.1.2 Plutonium**

A significant quantity of plutonium is 8 kg regardless of the isotopic mix. The amount of pebbles needed for this amount varies from 1,42,142 pebbles at 10 MWD/kg to 165,968 pebbles at 90 MWD/kg. This diversion must be detected within 1-3 weeks. The low end applies when the plutonium is not mixed with other elements since there is no reprocessing necessary to use it for a weapon. If the plutonium is mixed with other elements the timely detection interval will be on the high end because of the time necessary to separate the elements. Weapon-grade plutonium will have less than 7%  $^{240}\text{Pu}$  and a higher percentage of  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$  (see Table 1). Figure 5 shows that for the MPBR the quality of the fuel as potential weapon material decreases with burnup.

#### **4.1.2 Probabilities**

In order to determine whether or not the IAEA is fulfilling their duties in respect to detection two probabilities are discussed, the detection probability and the false alarm probability. The detection probability is more difficult to measure since it depends on knowing that a diversion was not detected. It is possible to determine the probability of detecting whether a fuel cask has been filled with dummy fuel. This would be calculated based on how many casks were checked in a random sample. The IAEA has a 90-95%

goal for the probability of detection. The false alarm probability is easier to ascertain, it is the probability that an event is detected as diversion, and then is found not to be. The goal for this quantity is 5%.

## **4.2 Considerations for implementation (Ref. 9)**

There are many things to consider when designing a safeguard system for a reactor plant. The physical structure and the type of nuclear material present encompass all of them. It is necessary to look at how much material in what form is present in each area of the facility and how someone might gain access to it. It is also important to think about possible ways a person could conceal the diversion in order to find ways to prevent it. Finding false records, or dummy fuel is a quick indication of diversion. A warning light should also go off if inspectors are only given restricted access, or any IAEA equipment such as cameras, locks, and seals, are tampered with.

## **4.3 Safeguard methods**

### **4.3.1 Nuclear material accountancy (NMA) (Ref. 9)**

The most basic method of safeguarding a facility is requiring a nuclear material accountancy (NMA). Careful records are kept of all nuclear material within the facility by designating material balance areas (MBAs). Measurements are made at strategic points (SP) throughout the plant. The total number of pebbles in the plant must correspond to the number present during the last period plus the amount added minus the amount shipped to spent fuel storage. The records kept by the plant are periodically reviewed and checked by the IAEA to make sure there are no discrepancies. The IAEA

also keeps track of the fuel shipped into and out of the plant in order to compare with the plant records.

The large inventory of pebbles would make counting each of them a tedious task. Instead of marking the pebbles and keeping track of them individual counting will take place by fuel cask and weighing containers. The fuel handling system does account for the balance of pebbles in the core. Each time a pebble is discharged into the spent fuel casks or the scrap container a new pebble is released into the core.

### **4.3.2 Containment and surveillance (C/S)**

#### **4.3.2.1 Locks and seals**

Locks and seals are two of the most basic ways to monitor access to the facility. Both can be placed on doors and casks to allow limited or no access. There are even some seals that can send an electronic signal when broken. Additionally seals can be used on welds. This would be helpful in the case of the MPBR where the pebbles are continuously travelling through piping. It would be more credible to claim that the piping had not been breached if not only were there no new welds, but also the weld seals on the old welds were not broken. There will still be a problem with verifying that diversion wasn't made from the pipes due to the fact that all the piping is not easily accessible. **(Error! Reference source not found.)**

#### **4.3.2.2 Cameras**

Cameras are a very important part of surveillance because it is impossible to be watching everything at all times. Most frequently the cameras that are used take periodic,

not continuous pictures. The time between snapshots corresponds to the time necessary to remove material from the area being monitored. Thus, if it would take a minimum of five minutes for someone to remove a cask from fresh fuel storage the cameras would take pictures every four minutes. The placing of cameras is also important so that the smallest possible number of cameras can cover the whole area.

#### **4.3.2.3 Inspections**

Inspections can either be either be scheduled or special. The planned inspections are generally for physical inventory verification (PIV) or during refueling, shipping, and other large movements of fuel. A PIV generally requires three visits to the reactor, one to begin the process, one to do the actual counting, and one to finish the PIV. There will generally be other scheduled inspections that correspond to the timeliness requirements for the fuel. Special inspections take place when some wrongdoing is suspected.

### **4.4 Safeguards for MPBR**

#### **4.4.1 Areas of concern (Ref. 5)**

Before determining what measures to take to protect the MPBR against possible fuel diversion it is essential to identify those areas that possess the most promise to a potential proliferator.

#### **4.4.1.1 New fuel storage**

There is a large amount of fuel present in the new fuel storage room, potentially 70 casks containing 1000 pebbles each. Considering the enrichment of the fuel and the mass of  $^{235}\text{U}$  per pebble it would be necessary to divert a minimum of 133,925 pebbles, which is 134 full casks, more than the total amount of fuel casks if the room is full, to obtain 75 kg of  $^{235}\text{U}$ .

#### **4.4.1.2 Scrap container**

The scrap container has a volume of  $0.1 \text{ m}^3$ . Each pebble has a volume of about  $110 \text{ cm}^3$ . This means a maximum of 884 pebbles can fit in the scrap can. This figure does not take into account the packing fraction due to the spherical shape of the pebbles, but it is a very conservative maximum value. All the fuel placed in the scrap container may not be spherical as it will be in other locations so it is necessary to consider absolute maximums. If all of the pebbles were close to maximum burnup these 884 pebbles would contain a total of 42.6 grams of plutonium. This is less than 1% of the 8 kg defined as a significant quantity of plutonium.

#### **4.4.1.3 Used fuel storage tank**

The used fuel tank in the ESKOM design is only used during defueling so the maximum number of pebbles that it will contain will equal the number of pebbles in the core, 360,000. This tank is built into the reactor facility. It is reasonable to expect these pebbles to have a level distribution of burnups, and thus an average amount of plutonium

per pebble based on the minimum and maximum amounts. From Table 4 the mass of plutonium per metric ton ihm is 0.8036 kg at 10 MWD/kg, and 6.296 kg at 94 MWD/kg, this gives an average of 3.5498 kg per metric ton ihm. Using this value the tank will contain a total of approximately 9.69-kg of plutonium. This exceeds a significant quantity, but it is also important to consider that the fuel in this number of pebbles will weigh more than 2.5 metric tons. Additionally it is important to note that inspectors will be present for the defueling process which decreases the likelihood of diversion from the tank.

#### **4.4.1.4 Spent fuel storage**

Each spent fuel storage tank has a volume of 78 m<sup>3</sup>. They each weigh 12 metric tons when empty and up to 80 metric tons when full. Since each one is larger than the used fuel storage tank each will contain more than a significant quantity of plutonium. In order to access the pebbles in the tanks it is necessary to remove a sealed cover. This procedure will not be possible on the plant site. (**Error! Reference source not found.**) Additionally, special equipment would be needed to transport just one of the containers.

#### **4.4.1.5 Piping**

Piping will not present a significant risk as an access point because it would be necessary to collect more pebbles than anyone could possibly carry at one time, excluding the radiation hazard of handling the pebbles.



#### 4.4.2 Methods for MPBR

An elaborate safeguarding scheme is not necessary for the MPBR due to the high volume of fuel necessary to create a weapon at any stage in the fuel cycle. However, some basic features are essential.

It will be necessary to have cameras to monitor all the areas mentioned in the previous section. Additionally there should be electronic seals placed on each of the spent fuel casks, and the used fuel storage tank that can detect any possible tampering. A lock on the door to the new fuel room should be sufficient when combined with cameras since such a large number of pebbles would have to be diverted.

Bi-annual inspections will also be necessary for PIV. Inspectors should also be present each time a shipment of fuel is received. They will count the casks and assume the content is the same as indicated on the invoice. During PIV the casks will also be counted, at this time the contents will be verified by a random sampling. Following the pebble counter at the entrance to the fuel handling system there will be a mechanism to sample the pebbles to make sure they are fuel and not replacement pebbles. Background radiation checks can be done on the spent fuel containers to verify that they contain spent fuel. **(Error! Reference source not found.)**

The only other concern for the MPBR is the counting accuracy. As each pebble passes into either the scrap container or the spent fuel container a new pebble is released into the system. It will be necessary to develop some technical means of determining whether or not the system can, or is being fooled.

## 4.5 Chapter Summary

The IAEA is concerned with the diversion of 75 kg or more LEU and 8 kg or more plutonium. In order to obtain this amount of material from MPBR fuel it is necessary to divert an enormous amount of pebbles. This fact makes safeguarding the plant an easier job because the diversion of this quantity of material would be a significant and detectable event.

The basic methods applied to all nuclear facilities will also be used for the MPBR. Cameras will be present throughout the facility, inspectors will bi-annually verify the inventory and be present during any large fuel movement, and locks and seals will be used to limit access to the fuel pebbles.

## 5. Conclusion

The MPBR does not pose a significant proliferation risk as compared to current LWRs. Even though the MPBR does operate with online refueling there are very few points where the fuel is accessible to a proliferator. Additionally, the number of pebbles at these points will be less than the amount needed for a weapon, except in the case of the spent fuel storage containers. However, these containers have added protection because they are built in to the reactor facility. Safeguard measures such as cameras and locks will be employed to increase the probability of detecting any possible diversion.

The high burnup and low enrichment of the MPBR fuel has a significant effect on its usability for weapon production. Table 11 and 12 show that in order to make either a plutonium or uranium weapon a minimum of 133,900 pebbles would have to be diverted. This number of pebbles is nearly twice the maximum amount stored in the fresh fuel room at any given time. If quality plutonium weapon material is the goal pebbles should be diverted at 20 MWD/kg which would require 758,365 pebbles. The minimum amount of pebbles needed for a plutonium weapon is 165,968, but this is at 90 MWD/kg where the plutonium characteristics are very bad for weapon construction. In addition to the large number of pebbles that are needed for a weapon, the fissile material has to be extracted from the weapon. This involves burning off the graphite matrix and removing the layers from around the fuel. Chemical reprocessing also needs to take place to separate the plutonium.

**Table 11: Pebbles necessary for plutonium weapon**

<b>Burnup MWD/kg</b>	<b>Number of pebbles</b>	<b>Percent of full core (360,000 pebbles)</b>
10	1,422,142	395%
20	758,365	210%
30	532,304	148%
40	415,131	115%
50	341,253	94.8%
60	288,236	80.1%
70	246,305	68.4%
80	211,993	58.9%
90	165,968	46.1%
94	181,520	50.4%

**Table 12: Pebbles necessary for uranium weapon**

<b>Burnup MWD/kg</b>	<b>Number of pebbles</b>	<b>Percent of full core (360,000 pebbles)</b>
0	133,928	37.2%
10	158,200	43.9%
20	191,939	53.3%
30	242,044	67.2%
40	323,283	89.8%
50	470,799	131%
60	797,392	222%
70	1,761,092	489%
80	6,194,081	1721%
90	29,791,667	8275%
94	59,869,663	15530%

Not only will an enormous amount of pebbles be necessary to have enough material for a weapon, but the plutonium is also difficult to use. The high  $^{238}\text{Pu}$  content causes the material to have a very high spontaneous fission rate as well as be very hot thermally. The plutonium extracted from the fully spent MPBR fuel is so hot that it could melt the high explosives if the weapon is not designed to dissipate enough heat. Additionally, the spontaneous fission rate is so high that the probability of a weapon yielding 4% of its design yield is less than 50%. Even though a bad weapon is still a weapon, the probability of a weapon made of this material having any yield is so low that it is a waste of time to try to design a weapon that will dissipate the huge amount of heat the material produces.

There are enough characteristics that are detrimental to using the MPBR fuel for a weapon that potential proliferators will look elsewhere for their fissionable material. A terrorist would not have the technology to extract the material from the pebble and then design a suitable weapon. A terrorist state will seek other locations to divert material that will be easier to handle and more reliable to use.

In the future, analysis of the spent fuel should also focus on the specific radiation hazard posed by the MPBR fuel in order to further prove the difficulty of handling the material both during diversion and while constructing a weapon.

## 5. References

- Ref. 1 Bäumer, R., et al. AVR – Experimental Technology High-Temperature Reactor: 21 Years of Successful Operation for a Future Energy. Düsseldorf: Association of German Engineers, 1990.
- Ref. 2 Bäumer, R., et al. Proposal for the Realization of Safeguards Hardware for the THTR-300. 1981.
- Ref. 3 Bäumer, R., et al. A Safeguards System for the THTR-300 and Optimization of Data Verification.
- Ref. 4 Cochran, Thomas. Burn. Computer software. Natural Resources Defense Council.
- Ref. 5 ESKOM. PBMR Technical Description, Section 8.11 Fuel Handling and Storage System.
- Ref. 6 Herring, J. Stephen and Phillip E. MacDonald. Characteristics of a Thorium-Uranium Dioxide High-Burnup Fuel. INEEL: September 2, 1998.
- Ref. 7 Herring, J. Stephen. Heat and spontaneous neutrons. Computer software. Microsoft Excel spreadsheet.
- Ref. 8 International Atomic Energy Agency. IAEA Safeguards: An Introduction. Vienna: IAEA, 1981.
- Ref. 9 International Atomic Energy Agency. IAEA Safeguards: Implementation at Nuclear Fuel Cycle Facilities. Vienna: IAEA, 1985.
- Ref. 10 Mark, J. Carson. “Explosive Properties of Reactor-Grade Plutonium.” *Science & Global Security* 4 (1993): 111-128.
- Ref. 11 Miller, Marvin M. Email to the author. 06 May 1999.
- Ref. 12 Owen, Paul, et al. “22.033 Design Project Report.” May 1998.

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