Anti-Proliferation Safeguard System for General Electric's PRISM Reactor Plant

by

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Submitted to the Department of Nuclear Science and
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Abstract

The proliferation resistance of a nuclear power plant has become an increasingly important issue due to the political climate of nuclear power at the present. Any new power plant that is constructed must be proliferation resistant and meet international standards set by the International Atomic Energy Agency (IAEA). In an age with a War on Terrorism and states not declaring their nuclear intentions, nuclear power needs to have proliferation resistance be a primary concern if nuclear power plants are to be built in the future.

The PRISM nuclear reactor system has been examined in this work with focus on the movement of nuclear fuel. The PRISM was chosen as the system to develop a proliferation safeguard system because of the literature that has been readily available for it and its potential use in the MIT Sodium Fast Reactor project. The safeguard system is based on the CANDU safeguard system with new components included to address diversion scenarios that were developed as part of this work. This work consists of developing those scenarios and the safeguard system. Also, research into the different components has been done.

Basing the system on proven work and showing that such systems can be adapted allows this system to be versatile in its use and implementation.

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Table of Contents

1. Introduction..5
1.1 Sodium Fast Reactor Project..5
1.2 Nuclear Weapons Proliferation..5
1.3 Objective...6
1.4 Methodology...7
1.5 Results...7

2. Methodology..9
2.1 System Basis: CANDU Safeguard System.....................................9
2.2 Developing Diversion Scenarios...11
2.3 Addressing Diversion Scenario...12

3. PRISM Design..12
3.1 PRISM Objectives and History..12
3.2 PRISM Facility Description...13
3.2.1 Reactor Module Description...13
3.2.2 Power Plant Description..15
3.2.3 PRISM Fuel..17
3.2.4 Fuel Handling System..19
3.2.5 Fuel Cycle Facility...21

4. Diversion Scenarios...24
4.1 Dummy Fuel Element...24
4.1.1 Creating the Dummy..25
4.1.2 Diverting From the Storage Area..25
4.1.3 Diverting During Transportation...26
4.2 Entire Cask Diversion...26

5. Safeguard System for the PRISM Plant..27
5.1 System Description...27
5.1.1 Plant Safeguards..28
5.1.2 Transportation Safeguards..30
5.1.3 Fuel Cycle Facility Safeguards..30
5.2 System Component Descriptions..31
5.2.1 Core Discharge Monitor..31
5.2.2 Spent Fuel Bundle Counter...31
5.2.3 Special Nuclear Material Portal Monitors and Weight Scales.......32
5.2.4 Geosynchronous Positioning System..36
5.2.5 Sealing Systems...37
5.2.6 Radio Frequency Identification Tags..41
5.2.7 Closed Circuit Television System..44
5.2.8 Weight Scales...44
5.2.9 Isotope Verification: Nuclear Resonance Fluorescence.................45
5.2.10 Satellite Surveillance..47

5.3 Addressing Diversion Scenarios..48

6. Conclusion...48
6.1 System Application..48
6.2 Work to be Done..49

References..50

1. Introduction

1.1 The Sodium Fast Reactor Project

The Sodium Fast Reactor Project (SFR Project) is currently a collaboration between faculty and students from the Massachusetts Institute of Technology, Ohio State University and Idaho State University for the purpose of examining current sodium cooled reactors designs and deciding which aspects of these designs to use in a new sodium fast reactor facility. The project is part of the Nuclear Energy Research Initiative (NERI) from the Department of Energy (DOE).

Currently there are 104 nuclear power reactors in the United States which provide about 20% of the electricity used in the country. (1) Electricity use in the United States may increase by as much as 75%. (2) Fossil fuels produce copious amounts of greenhouse gasses and nuclear power is an alternative to fossil fuel electricity production. The SFRP aims to design a new sodium fast reactor facility which may also serve as a burner of nuclear waste from light water reactors and therefore reduce the nuclear waste the facility produces and that of other nuclear power plants.

1.2 Nuclear Weapon Proliferation 2008

Nuclear Proliferation today has once again garnered a significant amount of attention in the media with the recent negotiations between North Korea and the United States concerning its nuclear weapons program and the possibility of Iran using its nuclear power program as a cover to develop its own weapons. At the present, eight countries have nuclear weapons while three of them (Israel, Pakistan, India) have not signed the Non Proliferation Treaty keeping proliferation a very real possibility.

So far, the civilian nuclear power infrastructure of a country will not be used as the basis of a nuclear weapons program though material derived from the power industry may be used in such a manner. More often a country will have dedicated nuclear weapons program that is visible to the rest of the world. The risk of proliferation comes from terrorist groups or the states that host them. The threat of proliferation from these groups can come from the diversion of nuclear material, misuse of nuclear technology or transfer of nuclear technology information. (3) Terrorist groups in particular would try to divert nuclear material for building a weapon and this drives national security concerns for the countries building new power plants and it drives the debate about the use of nuclear power.

Because of this, the Generation IV requisites include reducing proliferation. The Generation IV requisites are those to be met for new plants currently being developed and also include having the plants be economical, safe, and low waste producing. So designing an effective safeguard system for the nuclear material of any new nuclear power facility is essential for the security of the nation and the acceptance of nuclear power in the United States and abroad.

1.3 Objective

The Sodium Fast Reactor Project aims to implement measures against proliferation in order to make the selling and licensing of the facility much easier. Such measures can include the choice of fuel used at the facility and the core design and the instrumentation used to account for the nuclear material of this facility.

One of the sodium fast reactors that is being examined by the SFRP is the PRISM reactor by General Electric. This thesis outlines the most likely diversion scenarios and a safeguard system for the PRISM facility. The safeguard system is supposed to keep track of the nuclear material in the facility including waste from the PRISM facility and waste brought into from LWRs for the purpose of burning.

1.4 Methodology

The approach used to identify the diversion scenarios is that of taking the position of the proliferator who wishes to extract enough nuclear material from the SFR sodium reactor system to create a nuclear weapon. Doing so requires taking into consideration things such as time, shielding, transportation and amount of material.

Taking existing safeguard systems for different reactors in the United States and around the world and modifying them or adding to them for the purpose of is the approach used for the design of the PRISM safeguard system. The instrumentation from facilities such as the CANDU, ESFR and EBR-II can be applied to the PRISM. There are however, portions of the PRISM facility that are not addressed such as the tracking of vehicles that transport nuclear material in and outside the facility and safeguards for such situations are created to address them. Improvements to the way that nuclear material is accounted for are also made to this portion of the SFR Project.

1.5 Results

Two likely diversion scenarios are detailed in this thesis. The diversion of nuclear material has the intended purpose of building a fission weapon from the material at the facility. Plutonium content of the fuel pins is the primary goal of a diverter and the more plutonium the more enticing diverting the fuel pins is.

Diversion of a fuel transfer cask is the most likely scenario for a diverter to obtain the desired nuclear material. The transfer cask is transferred by a vehicle that can either move the cask to and from the reactor building to from an onsite fuel cycle facility or offsite. The vehicle can be commandeered or the driver can be coerced into diverting the vehicle with the nuclear material onboard to a location of the diverter's choosing.

A second diversion scenario that was addressed was where a diverter creates a dummy fuel pin that is used to replace a real fuel pin. A single or perhaps multiple fuel pins are switched out and are taken out of the facility on a vehicle or the material is carried by a person out of the facility. Enough material for a nuclear weapon would be taken out of the pins and diverted away before the facility administrators could notice that the pins had been switched.

The safeguard system for the PRISM includes measures from the CANDU and EBR II facilities. The two types of measures used are radiation detectors and tamper indicating seals on waste containers. The radiation detectors are either neutron or gamma ray detectors which verify that the fuel pins entering and exiting buildings in the facility are actual nuclear material that is supposed to be present. The tamper indicating seals show whether or not a person has tried to extract nuclear material from the waste casks located at the plant or (if located elsewhere) the fuel cycle facility.

New features for the facility include weight scales that monitor the presence of the nuclear material at all times and a dual geosynchronous positioning system (GPS) which tracks the position of the fuel assemblies inside the transfer cask and the vehicle which is transporting the nuclear material.

2. Methodology Description

The design of a safeguard system has been developed by basing the system on a previously used safeguard system and by developing diversion scenarios for the fuel used at the plant. Using previous safeguards allows one to use components which have been proven in the field before while diversion scenario development is developed through thinking about gaining nuclear fuel and what the diverter wishes to achieve.

2.1 System Basis: CANDU Safeguard System

The CANDU (CANada Deuterium Uranium) reactor is a heavy water reactor which uses natural uranium for fuel. The use of natural uranium brings about the need for daily refueling for the reactor. This constant fuel movement brings about the development of a safeguard system which can effectively track and account for the fuel of the CANDU. In addition to the safeguard system, Canada has agreed to the NPT and makes it a priority to show that its nuclear power program is for only peaceful purposes.

The tracking of fuel and diversion detection and prevent are the core of the safeguard system. The CANDU reactor does use natural uranium which would require a proliferator to take a large amount of fuel (over 2 tons). (4) This serves as discouragement for a proliferator from trying to divert fuel from the CANDU. The plants also have physical safeguards such as armed guards and physical barriers such as gates and walls.

The fuel of the CANDU reactor is removed from the core by a fueling machine which then moves it to a transfer bay. A spent fuel bundle counter (SFBC) then verifies the fuel through radiation detection and counts the bundles as they move from the core to the transfer bay. There are core discharge monitors (CDM) which detect radiation from the bundles in order to detect an unauthorized bundle movement from the core. Spent fuel is stored in the Spent Fuel Bay and monitored by radiation detectors or sealed using IAEA approved Atomic Energy Canada Limited Random Coil seals. The whole plant is monitored by security cameras. Figure 2.1 shows the CANDU plant and the implementation of the different safeguard equipment as the spent fuel bundles move through the plant.

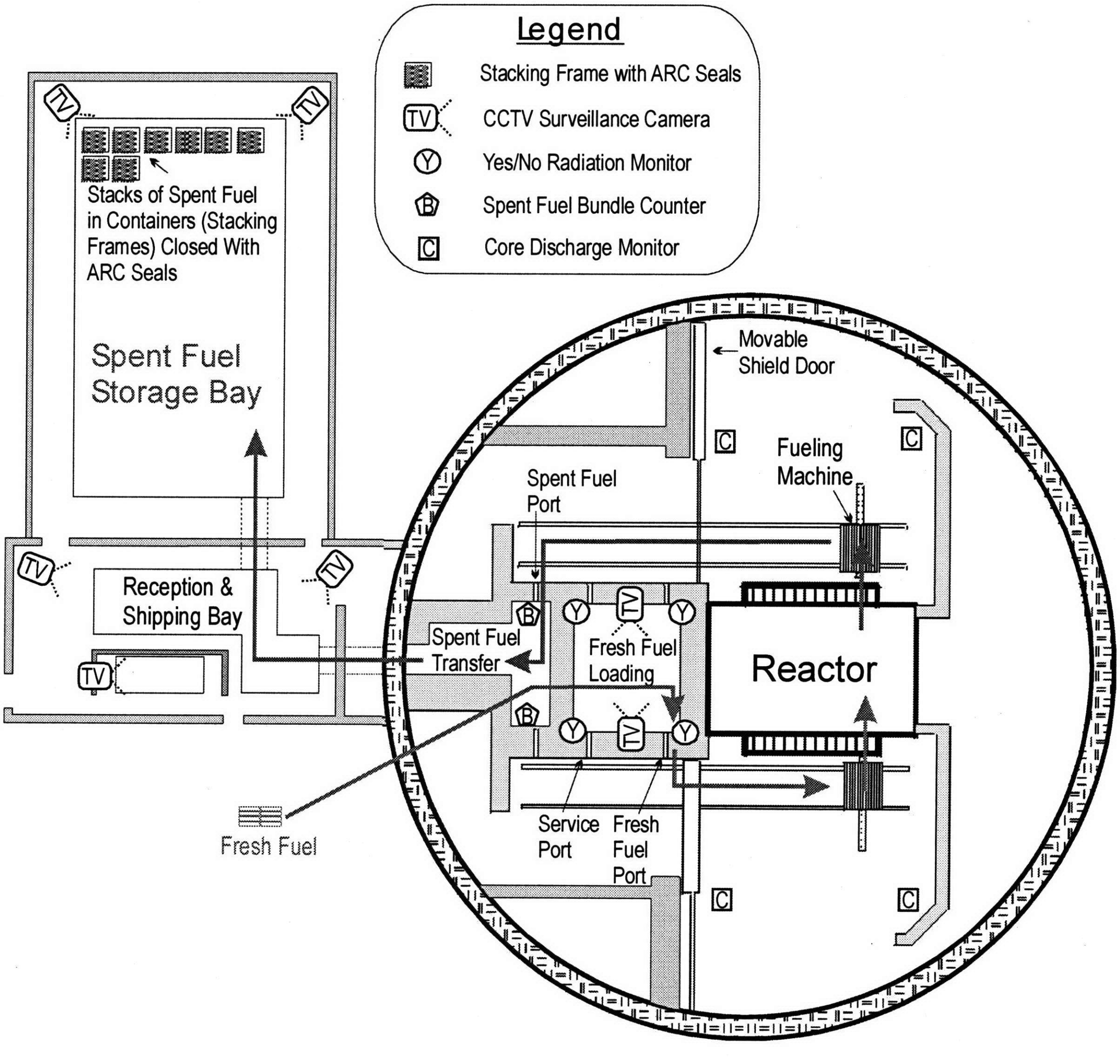


Figure 2.1 CANDU Safeguard System (4)

The PRISM safeguard system is based on the CANDU by taking the similarities of the PRISM plant to the CANDU and applying safeguards that are used in similar situations. The

CDM is the component that is taken directly from the CANDU. The SFBC, sealing systems and security camera systems are taken and new and improved systems are used in the PRISM safeguard system.

2.2 Developing Diversion Scenarios

The diversion of nuclear fuel at the PRISM plant is developed through consideration of the cost and benefit to the diverter, the ability and technology available to the diverter and the ease of access for the diverter.

The minimum amount of plutonium-239 that would be enough to produce a weapon is 8 kg. A PRISM fuel assembly contains about 9.94 kg of plutonium before entering the core and 7.68 kg after it has been burned. (5) Therefore losing two spent assemblies is unacceptable and tracking of fresh fuel and spent fuel is crucial.

A diverter may have nuclear material that is useable for a nuclear weapon and may be willing to sacrifice or risk that in order to gain more material that can allow for the completion of nuclear weapon. The diverter may also be willing to sacrifice people to achieve their goal. This then allows for a person to carry nuclear material on their body if they are willing to sacrifice themselves.

The other consideration that develops a diversion scenario is the resources that a diverter has a their disposal. The diverter may or may not have the technology to develop a nuclear weapon or they may not have the material to sacrifice for the diversion. But in the development of the diversion scenarios, we have assumed that both the technology and resources do exist for the diverter.

2.3 Addressing Diversion Scenarios

The diversion scenarios lead to the consideration of additional safeguards beyond those used at the CANDU reactor. New components are placed into the design in order to prevent the diversion of fuel from these scenarios.

3. PRISM Design

In order to be able to create a safeguard system for the PRISM plant, it is necessary to understand as much of the plant as possible. The emphasis is on the movement and storage of fuel throughout the entire plant as well as the processing facilities that may not be co-located with the plant.

3.1 PRISM Objectives and History

The Global Nuclear Energy Partnership (GNEP) was announced by Department of Energy Secretary Samuel Bodman February 6th, 2006. The plan is a partnership between different countries started by Japan, France and the United States which aims to reprocess spent nuclear fuel from other power reactors and do so in such a way that makes the fuel unusable for weapons purposes. (4) The GNEP vision needs a proven example that can demonstrate the viability of fast burner reactors. Support for the Advanced Burner Test Reactor (ABTR) depends on such a demonstration. The ABTR is a liquid sodium cooled fast reactor which is the technology that is the choice of the NRC. The ABTR needs a demonstration of transmutation of transuranic elements, safety, cost reduction and safeguards. (5) This demonstration has to come from a previous fast reactor design.

The Power Reactor Innovative Small Module (PRISM) is a liquid sodium cooled fast reactor designed by General Electric with help from Argonne National Labs. The PRISM was designed to provide a reactor which is reliable, has passive safety feature and is economically competitive with other power generating technologies. Because of it's similarity to the ABTR, the PRISM is used as for understanding strategies behind licensing a reactor that follows the Generation IV requisite and follows the GNEP vision.

The Clinch River Breeder Reactor (CRBR) program was authorized by congress to design a liquid metal fast breeder reactor in 1970. The program emphasized transmutation of transuranic elements along with defense-in-depth safety. The program required licensing after the 1974 Energy Reorganization Act but licensing was not completed when the program was terminated in 1983. At this time, the development of fast reactors was divided into two programs: the Integral Fast Reactor (IFR) and the Advanced Liquid Metal Reactor (ALMR). General Electric decided to pursue the ALMR which resulted in the PRISM. The Department of Energy submitted the Preliminary Safety Information Document in 1986 and the Preapplication Safety Evaluation Report in 1994.

3.2 PRISM Facility Description

3.2.1 Reactor Module Description

"The PRISM reactor is a small, modular, pool-type, liquid sodium cooled reactor which produces 471 MWt power." (6) Figure 3.1 is a cut-away of the standard reactor module. The modules are supposed to be small for the purpose of being constructed away from the plant site and being transported to the plant by rail. For a standard power plant, there would be three reactor modules at the facility with each reactor expected to have a 60 year lifespan. A power block consists of 3 reactor modules and would produce 465 MWe power. A plant would have up to 3 power blocks for a total of 1319 MWe power total. Each reactor module has its own intermediate heat transport system and steam generator. The reactors are all controlled by the same control center, maintenance facility.

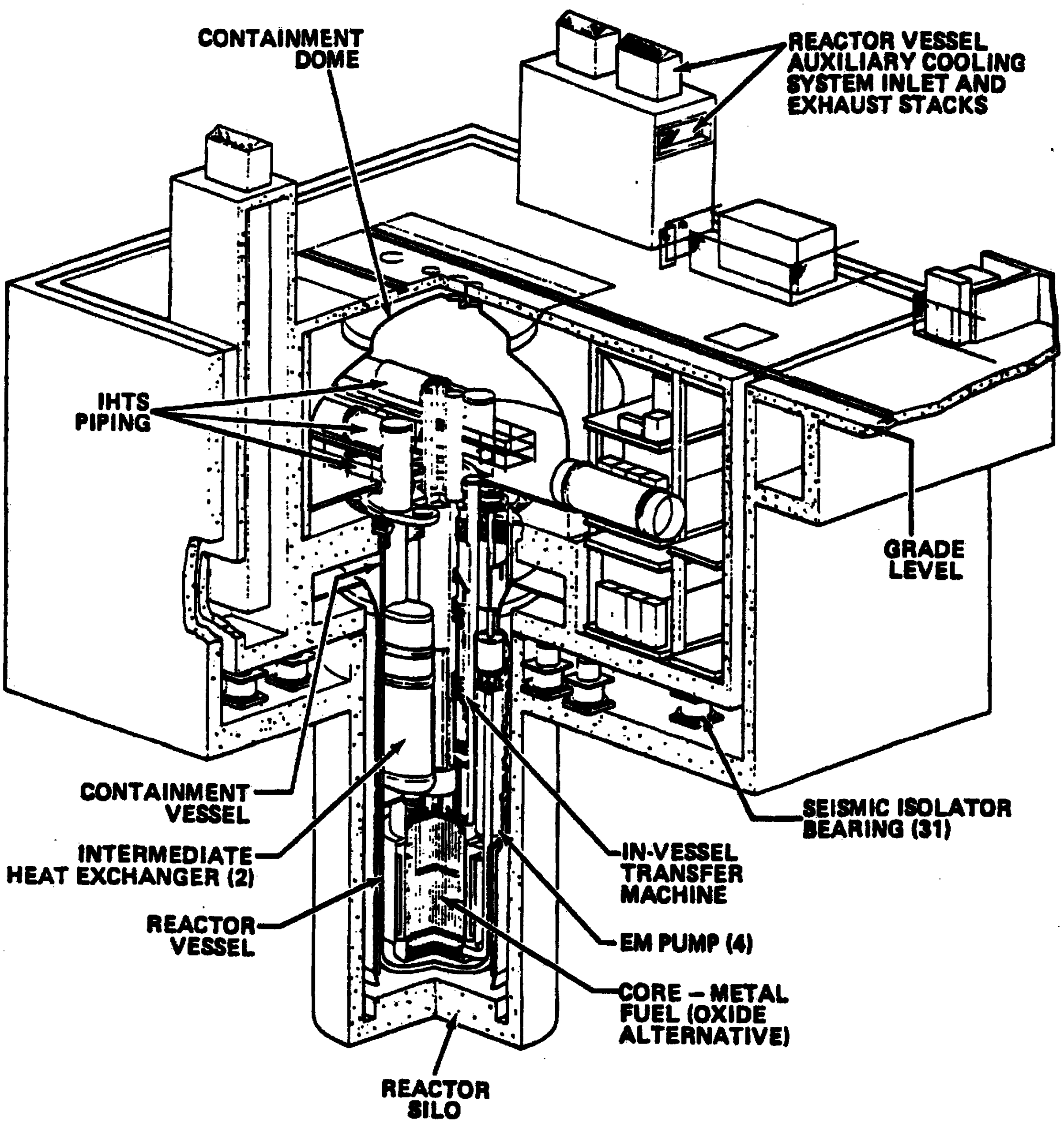


Figure 3.1 Reactor Module (8)

PRISM reactor modules are 19 m high and 6 m in diameter. (6) The reactor module and its components are seismically isolated in order to reduce horizontal movement and the silo is below grade. The vessel is 5 centimeter thick stainless steel and18.83 ft in diameter and 55 ft 7 inches high. There is a 38.6 centimeter gap between the reactor vessel and the containment vessel which is filled with argon gas. The gap is intended to provided the ability to perform a visual inspection of both vessels as well as contain a coolant leak. The closure head is a steel plate with a rotatable plug for refueling purposes.

The fuel used in the core is a metallic alloy (Uranium, Plutonium, Zirconium) in a HT9 stainless steel cladding. (5) The core's reactivity and power level are controlled by six independent control rods. One control rod is enough to shut down the reactor. There is an ultimate shutdown system at the center of the core to bring the reactor to shutdown if the control rods cannot be inserted.

The coolant is moved through the core by four electromagnetic pumps. The pumps are powered by a non-Class 1E ac distribution system. If the power system fails, a secondary offsite power system can run the pumps. There is no emergency ac system if the primary and secondary power systems fail the head is removed from the core through the intermediate sodium loop and through the intermediate heat exchanger.

3.2.2 Power Plant Description

Figure 3.2 shows a diagram for a standard power plant using the PRISM design. There would be 3 power blocks each with 3 reactor modules for a total of 9 reactors on site. The reactors would be below grade and all be controlled by the same control system at the control building. As shown in Figure 3.2, the reactors would each have their own steam generator and there would be a turbine facility for each power block. The total electrical power coming from the plant would be 1395 MW.

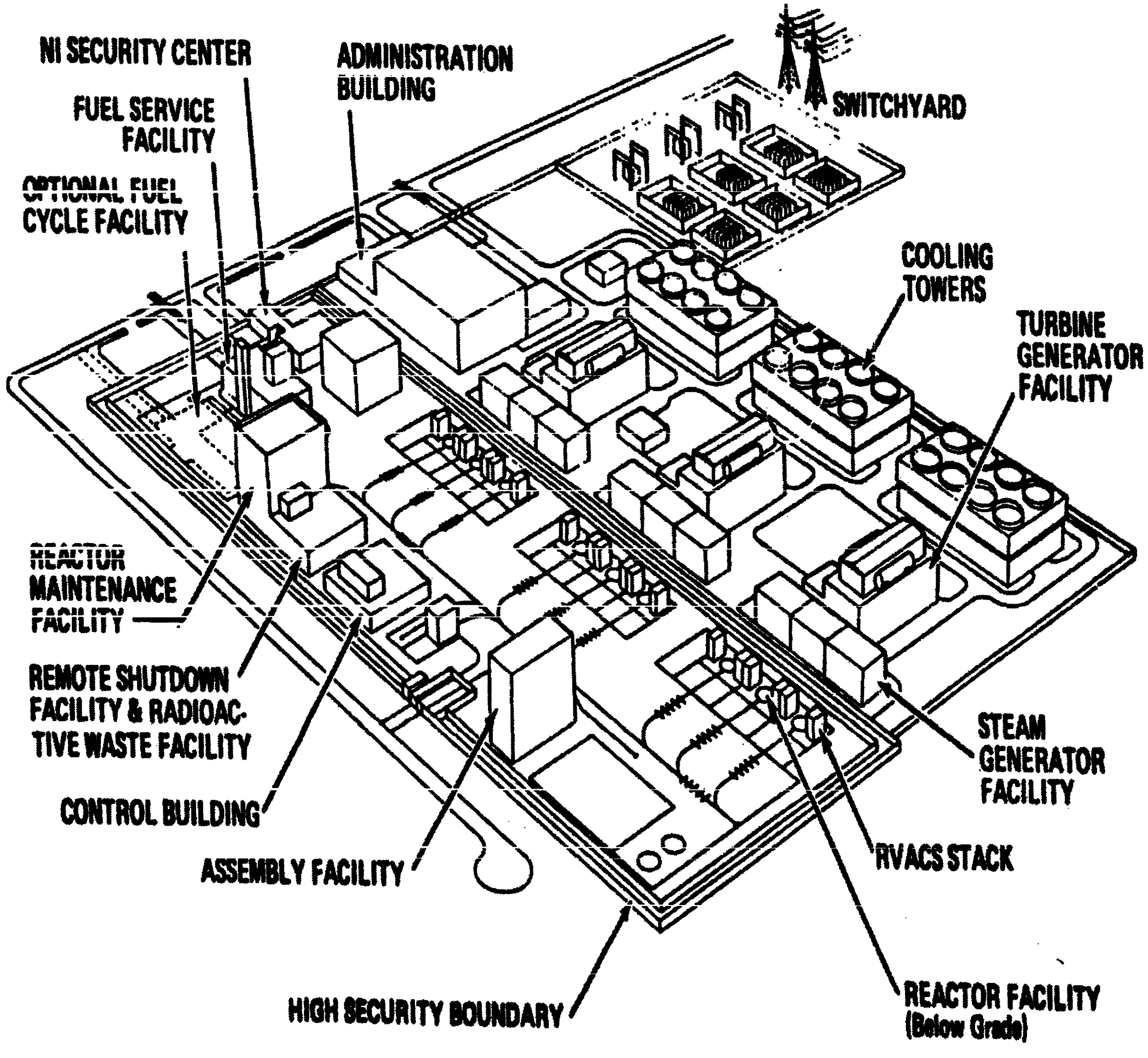


Figure 3.2 PRISM Power Plant (8)

The plant would have a security center where all close circuit television (CCTV) monitoring would be done in addition to monitoring of other security measures. There would be a high security barrier around the entire plant with exits at select points in the barrier.

Optional to the plant would be the fuel cycle facility. Because of the added cost to the plant, fuel cycle facilities may be used to service multiple plants. While it may be possible for a plant to have an on site fuel cycle facility, it would not be a likely scenario.

3.2.3 PRISM Fuel

Figure 3.3 shows the arrangement of the core for the PRISM reactors. The fuel is a metal alloy consisting of uranium, plutonium and zirconium in a clad made of the HT9 steel alloy. Each fuel assembly would be made of 331 fuel rods and the core would have a total of 42 assemblies. The core would also have 33 radial blanket assemblies, 42 reflector assemblies and six control rod assemblies. The radial blanket will have some assemblies replaced with gas expansion modules which are there to help with power shutdown in the event of coolant loss. (7)

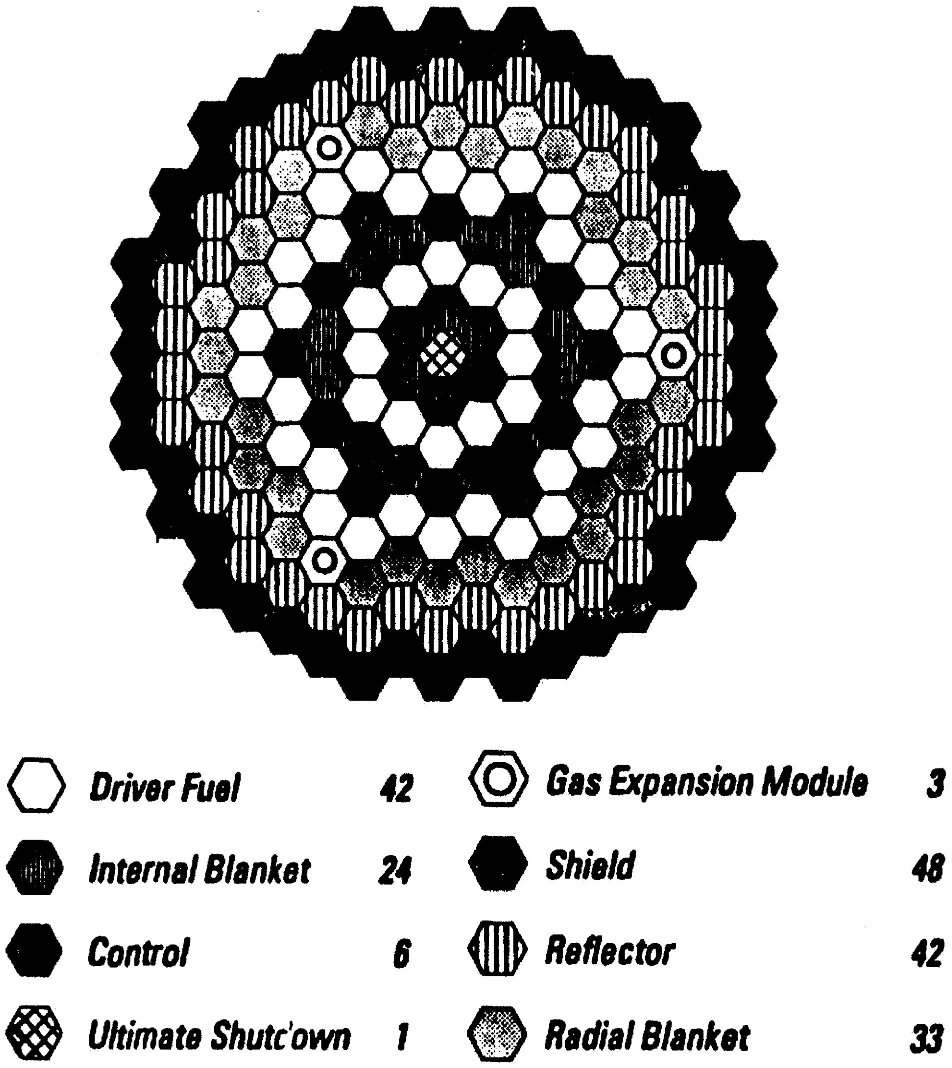


Figure 3.3 PRISM Fuel Arrangement (8)

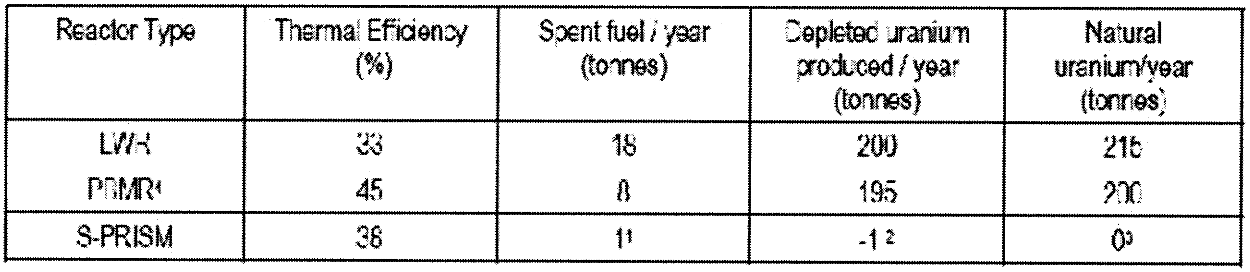
The fuel rods would use plutonium recycled from light water reactor (LWR) fuel. The fuel is designed to have a 4.5 year lifespan with fuel removed and replaced with a burnup of 135 MWd/kg. The blanket assemblies are designed to have a lifespan of 7.5 years and a max burnup of 55MWd/kg. (6)

The plutonium content of the fuel is very important to the proliferation resistance of the PRISM plant. In approaching the design of the safeguard system, the plutonium and uranium content of the fuel was focused upon because the assumption is made that the proliferator would be after fission weapons material. The threat of a dirty bomb is not considered to be major when compared to what a proliferator could do with fuel rods. The fuel from LWRs can be reprocessed using pyrometalurgical techniques (following the conversion of UO_2) to U metal but the composition of the reprocessed fuel has not been determined for the PRISM.

Metal fuel has not been thoroughly proven as metal fuel has so far has been used in prototype reactors such as the Experimental Breeder Reactor II (EBRII) which is why some of the measures against proliferation used at EBRII are being considered for the PRISM.

The PRISM is designed to have a thermal efficiency of 38% and have very minimal spent fuel produced. No depleted uranium would be produced because the PRISM reactor would act as a burner of the depleted uranium and other transuranic elements produced at other nuclear power plants. Also, it is believed the fuel source of the PRISM at the moment would be effectively inexhaustible because the fuel would be provided by reprocessing spent fuel from LWRs. Table 3.1 shows a comparison of these characteristics with other reactors.

Table 3.1 Reactor Fuel Comparison (10)



Reactor Type	Thermal Efficiency (%)	Spent fuel / year (tonnes)	Depleted uranium produced / year (tonnes)	Natural uranium/year (tonnes)
LWR	33	18	200	215
PBMR[4]	45	8	195	200
S-PRISM	38	1[1]	-1[2]	0[3]

3.2.4 Fuel Handling System

The fuel flow of the PRISM plant is show in Figure 3.4. The fuel is handled inside the reactor module at all times by the in vessel transfer machine (IVTM). A fuel assembly is transferred to the reactor by means of a portable fuel enclosure which also acts as a transfer enclosure for spent fuel assemblies. The assembly is placed in the core and after it completes its 4.5 year lifespan, it is removed and placed in a temporary storage position for a year after which it is take out of the reactor module and taken to the fuel cycle facility. Here the fuel assemblies are disassembled and reprocessed to make more fuel for the reactor with waste being stored at the facility.

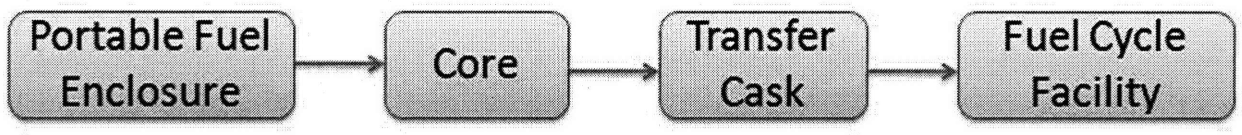


Figure 3.4 Fuel Flow in the PRISM

The reactor refueling system (RRS) is designed to operate for the entire 60 year lifespan of the plant with refueling occurring every 18 months and with the process taking up to 22 days. At this point, the RRS design is only conceptual and the design can change. (7) The RRS is comprised of the fuel handling system, the transport system and the shipping system. The RRS is designed to handle the fuel through its entire run in the plant. When refueling occurs, the reactor is shutdown and the sodium cooled to 480 K.

Figure 3.5 shows the progression of fuel through the reactor module with some safeguards. A new fuel assembly is taken into the reactor module by way of the transfer cask which is in the portable fuel enclosure. A fresh fuel pin is lowered into an in-vessel transfer position and then taken by the in-vessel transfer machine and moved into an empty position in the core. A spent fuel assembly is moved into an in-vessel storage position. Here the assembly will stay for a year to reduce the decay heat coming from the assembly. A PRISM reactor can store up to 22 assemblies at one time in the temporary storage above the reactor core. After spending a year above the core, the spent fuel assembly is moved to the transfer position by the IVTM and then it is moved into the transfer cask. This process is similar to the way other assemblies in the core are handled but the other assemblies do not need to spend a year in temporary storage above the reactor.

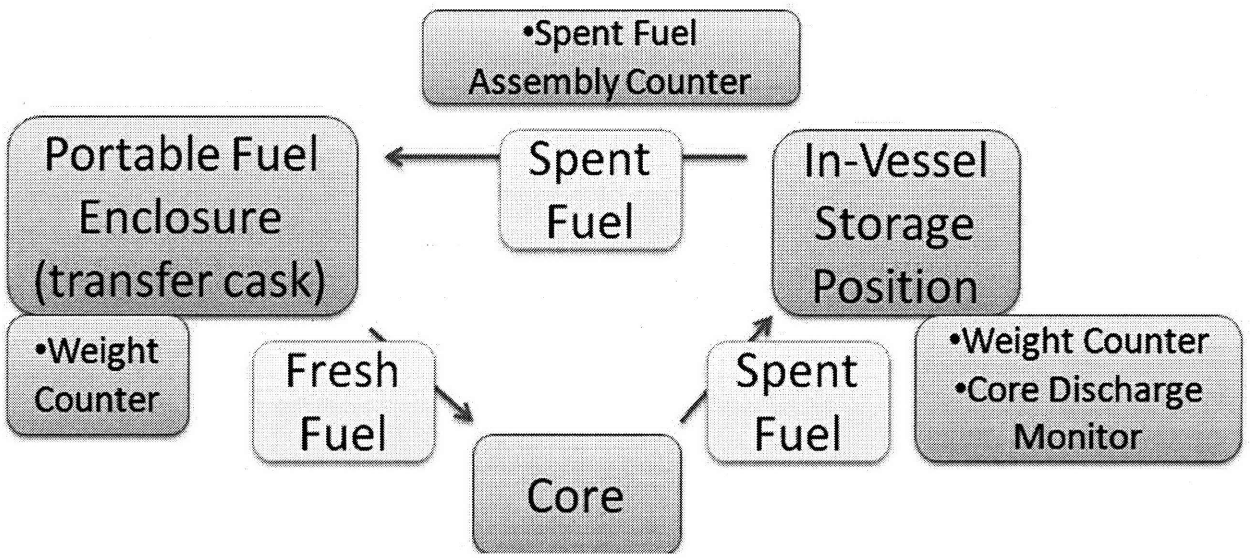


Figure 3.5 Fuel Through the Reactor Module with Safeguards

The refueling enclosure would contain the transfer cask and would be moved by the cask transporter. A driver would then take the cask transporter to the fuel cycle facility which can be located at the same plant or to the closest one available. As stated before, fuel cycle facilities would not be located at all PRISM based plants and so the spent fuel assemblies would be transported from one plant to another with a fuel cycle facility. This would place the fuel assemblies out of the secure plant location.

3.2.5 Fuel Cycle Facility

The reprocessing of spent fuel from light water reactors (LWR) is the source of fuel for the new generation of fast liquid metal reactors (LMR). After production of LMRs has increased, the reprocessing of spent fuel from LMRs would be another source of fresh fuel. Figure 3.6 shows the flow of spent fuel and fresh fuel to and from LWR, LMR, and spent fuel reprocessing facilities (SFRF). The reprocessing of spent fuel depends on its source. LWR spent fuel is reduced from its oxide form into a metallic form. Afterward, it is put through the pyroprocess developed by Argonne National Labs (ANL). The reprocessed fuel has three "streams" coming from it. The first contains the transuranic elements to be burned in the fast reactors, the second contains the uranium and plutonium used to fuel the PRISM reactor, and the third has the waste from the process such as fission products. The fuel cycle study indicates that only 0.1% of the transuranics will go into the waste stream. (8)

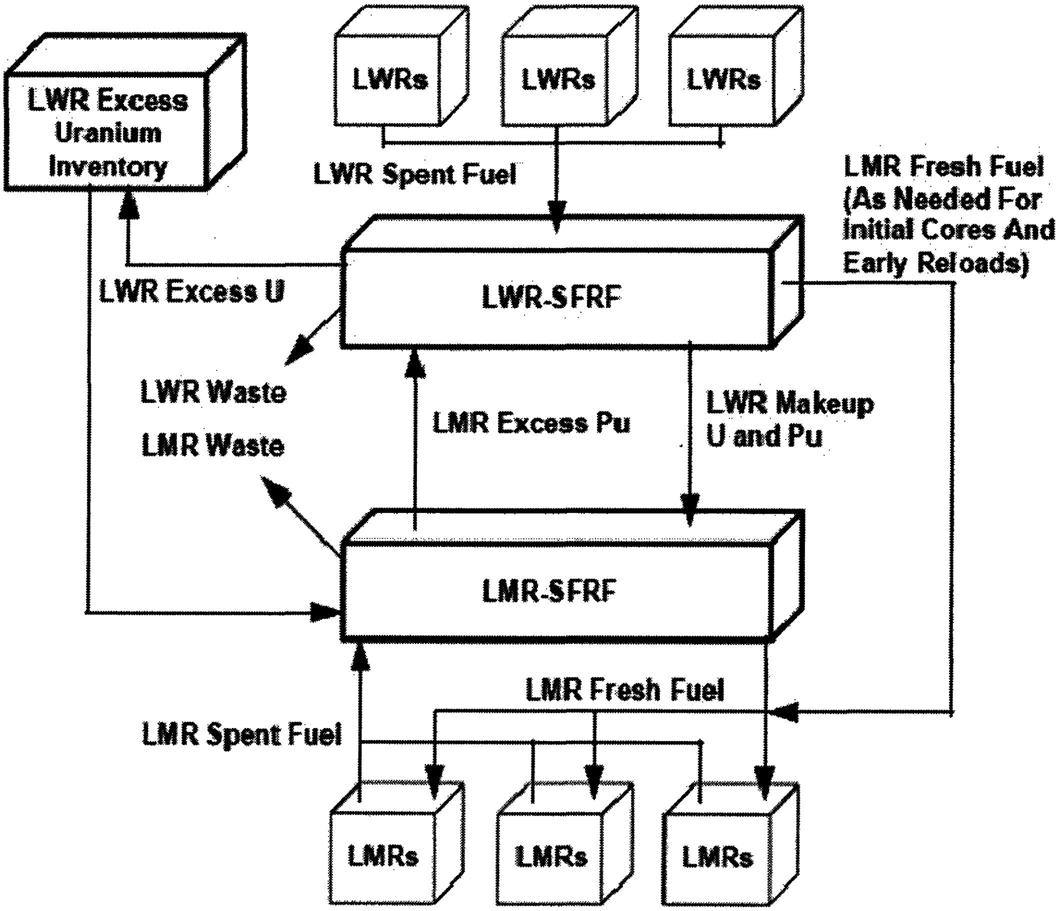


Figure 3.6 Spent Fuel Flow from LWRs to LMRs (10)

The LWR spent fuel pins and reprocessed in very much the same manner as the LMR fuel pins save for the reduction to metal. Figure 3.7 shows the process through which spent fuel pins go through to extract fresh fuel and waste.

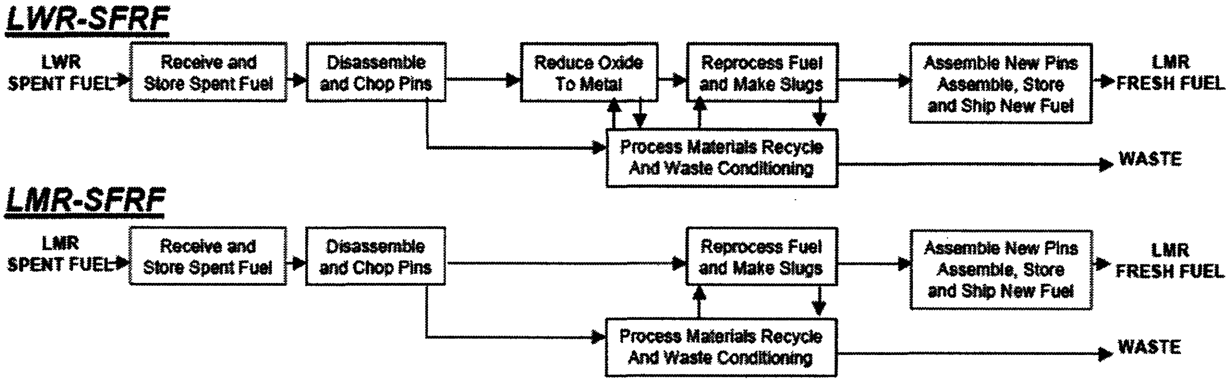


Figure 3.7 Fuel Reprocessing (10)

The fuel pins are disassembled in a temporary storage. The fuel pins are removed from the assemblies and then any assembly material that is not nuclear is disposed of. The pins are then chopped up so that they can be processed. The chopped pins are placed in an anode basket and for the pyroprocess, it is expected that the baskets will contain about 10 kg of plutonium. Figure 3.8 shows the progression of fuel and waste as it goes through the pyroprocess. The electrorefiner separates the uranium, plutonium and other actinides (TRU) from the spent fuel. The anode product is then transferred to the cathode processor where the fission products, typically salts, are removed. The mixture of uranium, plutonium and actinides is then sent off be processed into new fuel. The uranium/plutonium and TRU metal is melted into new fuel ingots which are then made into new fuel pins. After being moved to the receiving cell at the fuel cycle facility, the pins are put together into fuel assemblies and ready to be used in the PRISM reactor.

The waste that is extracted from the process is then stored at the facility. The waste consists of the steel cladding that encases the fuel and the fission products removed from the fuel during processing. Fission products are converted into a ceramic waste for. Both types of wastes are stored at the facility.

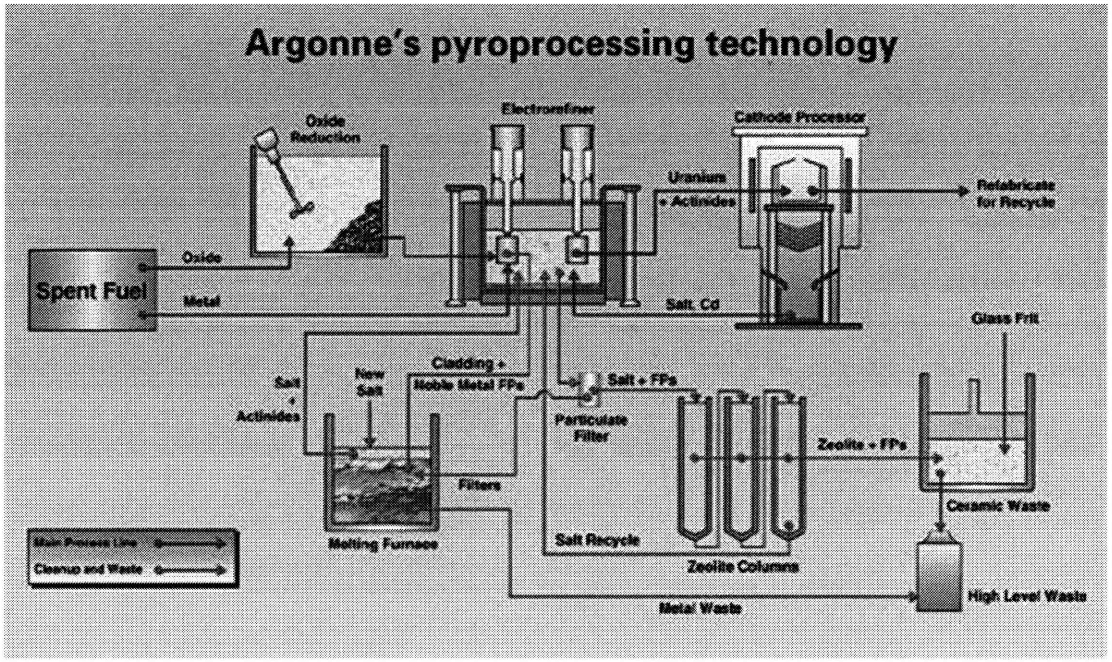


Figure 3.8 Pyroprocessing (11)

4. Diversion Scenarios

In order for a diverter to have the potential for creating a nuclear weapon, they must successfully obtain a minimum of two fuel assembly from the PRISM plant. Two scenarios have been developed for the most likely points of diversion of the fuel.

4.1 Dummy Fuel Element

A diverter may develop a dummy fuel element in order to replace a fuel assembly that they may try to steal. The purpose of the dummy fuel element is to allow for the diversion of a real fuel assembly to occur without notice. Doing so would require the diverter to have access to the fuel assemblies and know the different details and features of the assemblies. Also, if the diverter managed to remove a fuel assembly and replace it with a dummy, this could allow the diverter more time to create a nuclear weapon or sell the fuel to someone who has the technology to build the weapon without having the IAEA for them.

4.1.1 Creating the Dummy

A diverter must create a fuel element that would have the same mass, radiation levels and decay power as a normal spent fuel assembly. There are different dummies that a diverter may to choose to use, such as one assembly that only looks like a real assembly and would appear to fit into the assembly storage and meets all of the criteria listed above. The dummy could be made mostly of nuclear waste products, useless transuranics or fission products. It would then be coated with a uranium and plutonium mix that would allow it to have a similar radiation signature to a real fuel assembly. The mass, radiation signature, isotopic composition and possibly heat would be very similar.

4.1.2 Diverting from the Storage Area

The dummy element would replace a real assembly at a point where the diverter may be able to have access to the fuel assemblies. The points at which this could occur would be the temporary storage of spent fuel in the reactor building or the transportation of fuel from the facility.

A dummy element inserted into the fuel cycle at a point where fuel is sitting for up to a year allows for a few potential advantages. Firstly, the fuel is not moved from its location for up to a year and the diverter may be one who could gain access to the IVTM and move a fuel pin out of the storage area. The time given to the fuel for cool down would allow a diverter days or months to move the fuel assembly out of the facility. The time would also be crucial because it may allow more time for the diverter to get the fuel out before someone notices the dummy element is not real. The diverter would then have to move the assembly out of the reactor building and out of the facility. This can occur through use of a transporter with shielding for the radiation of the element.

4.1.3 Diverting During Transportation

An alternative and more likely diversion point would have to be a diverter making a switch after the fuel has been loaded into a transporter and taken from the plant or to the plant. At some point between the fuel being loaded until is unloaded at a different site, a diverter may have the transporter stopped and attempt to remove a fuel assembly and then replace it with the dummy element. The outside diversion means the diverter does not have to go through the physical barriers such as armed security personnel and walls to get away with the fuel and therefore diversion is easier from this point.

4.2 Entire Cask Diversion

The diversion scenario which results in the most gain for the diverter is that where an entire cask loaded with a load of fuel assemblies is stolen. This would allow the diverter to ensure that enough nuclear material would be obtained for a nuclear weapon (perhaps multiple ones) and also as before, access to the cask would be much easier if they try to divert the fuel outside of the facility during transportation. The main disadvantage to this scenario, for the diverter, is that such a diversion would not go unnoticed for very long so time to sell or build the weapon would be critical.

The diverter would either try to take control of the transporter and take it to a secured location or try to replace the transporter cask with another cask that would serve as a sort of dummy cask. It would then be possible for the diverter to have more time to escape with the fuel and sell or create the weapon themselves.

5. Safeguard System for the PRISM Plant

5.1 System Description

The PRISM safeguard system has been developed through following the fuel through its movement in the plant and its transfer to the fuel cycle facility. The components of the system can serve as either, barriers to the diversion of fuel or serve to detect diversion or attempted diversion. The system would also have physical barriers such as walls or fences with entry to the plant at only selected points. Armed security would also be present at the site and would be provided at the discretion of the host state. Figure 5.1 shows the plant and fuel cycle facility and the safeguards in place for the fuel. The transportation for fuel to a fuel cycle facility not co-located with the plant would also have safeguards implemented into it. There are multiple components for certain points for redundancy.

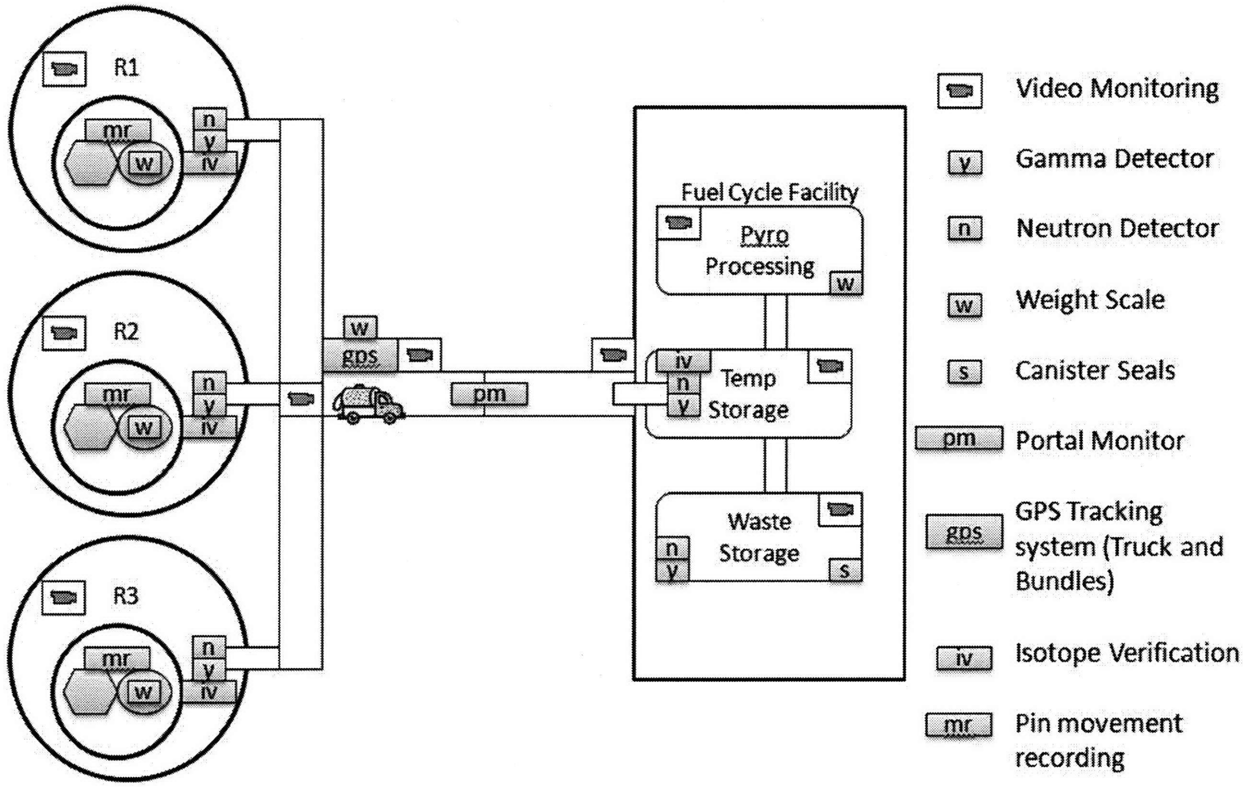


Figure 5.1 PRISM Safeguards

5.1.1 Plant Safeguards

The entire plant would be monitored by camera and this would be the first defense against diversion. Refueling occurs every 18 months. The fuel assemblies are taken out by the IVTM and moved into a storage area on a storage rack as shown in Figure 5.2. There are radiation detectors in the reactor building to detect if fuel is moved out of the building through unauthorized exits. These core discharge monitors are mounted on the walls and ceilings of the building. As the fuel is moved to the storage area, it is loaded onto the rack. The rack would be on a weight scale. The scale would observe the weight of the fuel at all times during the one year cool down period. This serves as a way of monitoring the presence of the fuel at all times. The IVTM's motions are recorded and if the weight of the rack does not match the anticipated weight given by the IVTM's motions, an alarm would sound. If a pin is moved, the scale would see this movement immediately and so moving fuel without authorization would not be possible.

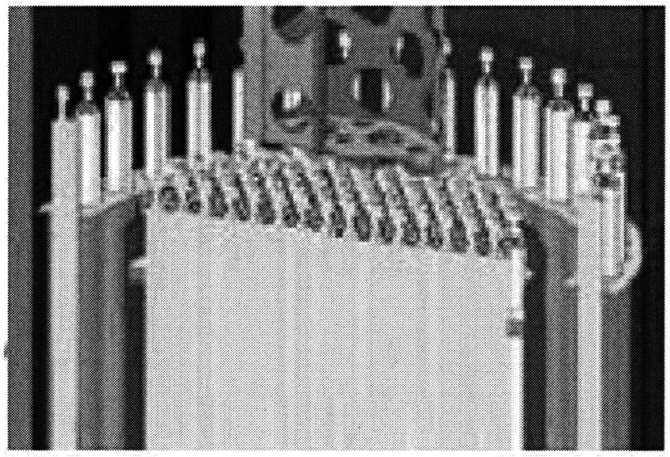


Figure 5.2 Storage Rack (5)

The fuel is loaded into a transfer cask to be taken to a fuel cycle facility and at this point, a spent fuel assembly counter, would verify the radiation signature of the fuel as it is loaded in. This system can eventually be replaced by Nuclear Resonance Fluorescence which can verify the isotopic content of the fuel. Before being loaded for transfer, the assemblies would have radiofrequency identification tags placed on them to allow for easier tracking and verification. The transfer cask is then loaded onto the cask transporter and taken out of the plant to the fuel cycle facility. As shown in Figure 5.1, this would occur for all three reactors in each power block. They would all have the same safeguard components installed in them.

In addition to the physical barriers of the plant and fuel cycle facility, the entry points of these facilities would have portal monitors installed for both vehicles and personnel. The personnel monitors would have weight scales on them which would monitor any unusual changes in weight of people who may try to carry shielded nuclear material out of the plant themselves. The portal monitors detect gamma and neutron radiation coming from nuclear fuel.

If a power outage occurs, the monitors have internal batteries allowing them to operate for several hours. If that fails, the security personnel can manually inspect the people or vehicles trying to enter or leave with handheld radiation monitors.

5.1.2 Transportation Safeguards

The most vulnerable aspect of the fuel movement is during transportation. Fuel from LWRs and fresh fuel from the fuel cycle facility must also be accounted for.

The transport cask and the transporter would be fitted with GPS tracking systems to allow the security center of the plant to track the position of the fuel. Both the transporter and cask must be located together. There would be electronic seals on the cask to ensure that the cask is not opened during its time outside of the plant. If the host state has the infrastructure in place, satellite monitoring of the transporter could provide visual confirmation of location and activities of the cask and transporter.

5.1.3 Fuel Cycle Facility Safeguards

The fuel cycle facility would also have portal monitors and weight scales installed at the entry points. The facility would scan the identification tags place on the fuel and also verify them using radiation detectors or the nuclear resonance fluorescence machine. The waste storage of the facility would be monitored by radiation detectors and also have tamper indicating seals on the waste containers. The entire facility would also be monitored by camera.

5.2 System Component Descriptions

5.2.1 Core Discharge Monitor

A core discharge monitor (CDM) would be installed on near the core in the in-vessel storage area. Along with the weigh scale, the CDM would monitor the removal of fuel assemblies from the reactor by the IVTM. It is small enough to be mounted anywhere in the storage area and the reactor building. The system insures that unauthorized fuel removal is recognized immediately.

The CDM verifies the fuel assemblies as they are removed from the core and kept in storage for one year. The system consists of "fission and ionization chamber, preamplifiers for the fission chambers and a GRAND electronics package." (9) The system is designed to be unattended and there are currently 25 systems installed in CANDU reactors. (10) It is one of the systems that is being taken from the CANDU safeguard systems and being used in the PRISM safeguard system because of its proven record and satisfaction of the IAEA safeguards.

The CDM would have its readings compared to the recorded movements of the IVTM. If the CDM measures changes in the intensity of the radiation from the fuel that are not in keeping with cool down, and the IVTM does not show movement of fuel assemblies.

5.2.2 Spent Fuel Bundle Counter

The Spent Fuel Bundle Counter (SFBC) is taken from the CANDU safeguard system as well. The SFBC is designed to take in a fuel assembly and use He-3 radiation detectors to verify the bundles as they are moved from the storage position to the transfer cask in the portable fuel enclosure. (11) The counter uses tungsten shielding for the He-3 detectors to protect them from the intense gamma radiation coming from the spent fuel.

The counter's measurements verify that the fuel is present as it goes past the detectors. This prevents a dummy element from going unnoticed. The SFBC would work in conjunction with the isotope verification machine located in close proximity.

5.2.3 Special Nuclear Material Portal Monitors and Weight Scales

One of the more common ways to secure nuclear material at a plant is to use monitors that detect the presence of nuclear material carried by vehicles or people leaving the plant. Portal monitors have been used at national laboratories that house nuclear materials and have been very successful at preventing the diversion of nuclear material. (15) These same monitors can be used at borders of countries and entry points such as ship yards to detect the flow of nuclear material. The monitors can be gamma or neutron radiation detectors or a combination. These "monitors collect and analyze radiation data emitted by weapons grade or reactor grade nuclear material." (9)

Canberra and Los Alamos National Laboratory have developed these monitors with specific problems in mind. First the monitors must be sensitive enough to detect the special nuclear material. There should also be as few false alarms as possible to allow operations at a plant to run smoothly and not unnecessarily detain people and vehicles not carrying any unauthorized material. The monitors are also designed with tampering prevention features in mind. There are also other considerations that must be made such as the isotopic content. For the PRISM, the plutonium is reactor grade while the uranium is natural uranium. The reactor grade plutonium is harder to detect because of the higher radiation detection limit with these monitors and the natural low enriched uranium is harder to detect because of its lower gamma radiation emission when compared to enriched uranium. The PRISM uses metal fuel and this must be considered when setting the detection limit of the neutron and gamma detectors. Neutron detectors are considered for use in the portals because high density shielding materials do not attenuate fission neutrons as much as gamma rays. Background radiation is also a consideration. Elevation is a strong factor when considering the detection limit and so again combination neutron/gamma detector portals can be used to prevent false alarms.

The vehicle and personnel portal monitors are very similar but their configurations vary. Figure 5.3 shows a vehicle portal monitor. The monitors work by comparing the measurements taken when a vehicle or person is in the monitor to a threshold measurement set when the monitors are empty. The Sequential Probability Test Ratio is used for the monitors. The portal controller examines small count intervals and these intervals are compared to two thresholds: background and background plus that of a transient. There is a variance analyzer in the monitor which will sound an alarm if changes in the background are larger than expected. The alarm of the monitor will sound when the background passes a set upper or lower limit threshold and if the difference between background and the intervals exceeds are set threshold.

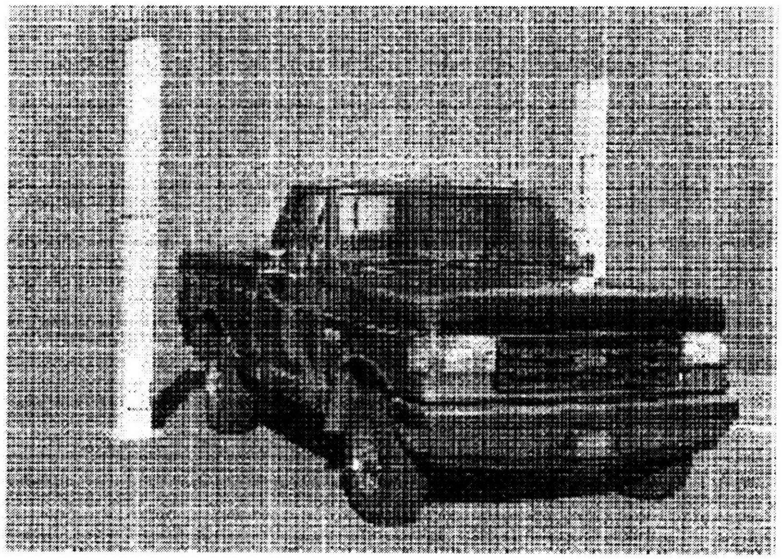


Figure 5.3 Vehicle Portal Monitor (15)

The monitors have low noise electronics that also prevent false alarms. There is also battery backup in the monitors that allow for them to operate continually for several hours in the case of a blackout. The monitors themselves are encased in a weather-tight low Z material to prevent neutron and gamma ray attenuation. There are doors that allow access to the detectors but are secured with key locks and tamper indicating devices (TID) which show any attempt to tamper with the electronics inside. There is also a "secured communication port (which allows) authorized personnel to set and change the threshold values". (9) The monitors are also designed to have easily replaceable mechanical and electronic parts.

The two detectors used in these portal monitors are gamma and neutron detectors. The detectors used depend on the nuclear material that is to be monitored for and what kind of monitor one will be using: either a personnel or vehicle monitor.

Gamma ray detectors are used in the portals to detect gamma rays from enriched uranium or plutonium. Background is reduced by having the scintillators shielded with lead on three sides. The scintillation detectors are made of plastic because their ability to capture much of the gamma radiation from plutonium and they also cost less than equally effective sodium based scintillators.

Neutron detectors in the monitors are made of "He-3 proportional counters inside a hollow, high density polyethylene enclosure" to detect thermal neutrons from plutonium. The neutron detectors would be instead of gamma detectors because gamma ray backgrounds can fluctuate greatly and neutrons are much harder to shield for.

For the PRISM facility, one would be concerned with guarding spent fuel and fresh fuel pins which would contain depleted uranium and plutonium. The best choice of monitor would be a combination monitor which uses both neutron and gamma ray detectors. These monitors will however be less efficient because two detectors means more detection limits and this opens up a great possibility of false alarms.

In addition to these detectors, another suggestion in this thesis that the monitors be combined with metal detectors and weight scales. The metal detectors in personnel monitors would be able to not only detect weapons such as knives or guns going in and out of the PRISM plant, but also detect metals being used to shield plutonium. High Z metal would be used to shield gamma rays but if the metal is not thick enough, the gamma rays would be detected. However, the metal detectors would prevent this from being a problem.

The weigh scales would serve the purpose of monitoring the weight of people entering and leaving the PRISM plant. A worker would register a weight with the plant database from which they could not deviate from by more than a set limit. A limit of about 5 kilograms would be reasonable because the weight of the nuclear material containing enough plutonium (8 kg) to produce a weapon would be about 20 kilograms. If a person does go over the limit, they must be inspected with hand monitors and their new weight registered. The weight of the person entering the plant would be registered for the day and the weight when they exit may not have a difference of maybe a few kilograms. These procedures ensure the person is not entering or leaving with unauthorized materials. Their personal belongings would be inspected separately from them. This weight monitoring would necessitate a database of all personnel to be used. The database of weights can be tied into the entry system that the facility chooses to use. Card scanners are frequently used at many facilities. When a worker scans their personnel card to enter the facility as an authorized worker, the weight of the person entering can be brought up as they are about to step into the weigh station which would be under the portal monitor. So an alarm would sound if the weight of the person is not matching the found in the database, metal is detected or nuclear material is present.

5.2.4 Geosynchronous Positioning System

As indicated in figure 5.1, there are several safeguards used to monitor the movement of fuel within the cask transporter. The cask transporter moves the fuel between the reactor building and the fuel cycle facility. The fuel cycle facility, however, is optional for the PRISM plant and this means that transportation of spent fuel from the reactor and fresh fuel from the fuel cycle facility. This allows for diversion to occur outside of the plant and fuel cycle facility which is one of the more likely points of diversion because of the perceived lack of monitoring.

The cask transporter and cask would both be fitted with Geosynchronous Positioning Systems (GPS). This safeguard is a component that has not been proposed or used elsewhere and is being made part of the design for the PRISM plant. The cask would have the GPS on the outside of it to prevent radiation from the fuel from damaging it and to allow the signal to be transmitted. The cask transporter would have its GPS in a location to be determined. It would be in a place accessible for repair or replacement and not dependent on the vehicle. The GPS would transmit the position of the cask and the cask transporter at all times to the plant control center as well as the agency tasked with monitoring nuclear fuel movement in the country (ie. The NRC in the United States).

The prevention of the cask being transferred onto another vehicle is very important and one of the diversion scenarios that results in the most gain for the diverter. Tracking the position of the cask and cask transporter independently will allow the agency and plant security center to verify that the cask has not been loaded onto another vehicle. Both positions shown the GPS cannot deviate more than a specified amount (to be decided by the security center and nuclear regulating agency) otherwise, the system will indicate the fuel may be in the process of being diverted.

The GPS system must be able to transmit its signal so it will not be housed in thick metal to prevent tampering. Instead, the GPS system would be locked in a tamper indicating sealed box. An electronic seal would be similar to what is used for the sealing of the transfer cask and the waste casks at the fuel cycle facility. The electronic seal will show tampering with the box and if the seal is broken, a signal will be sent to the security center and the country's nuclear agency alerting them of the tampering which can indicate possible diversion. Sealing technology to be used is described in the next section.

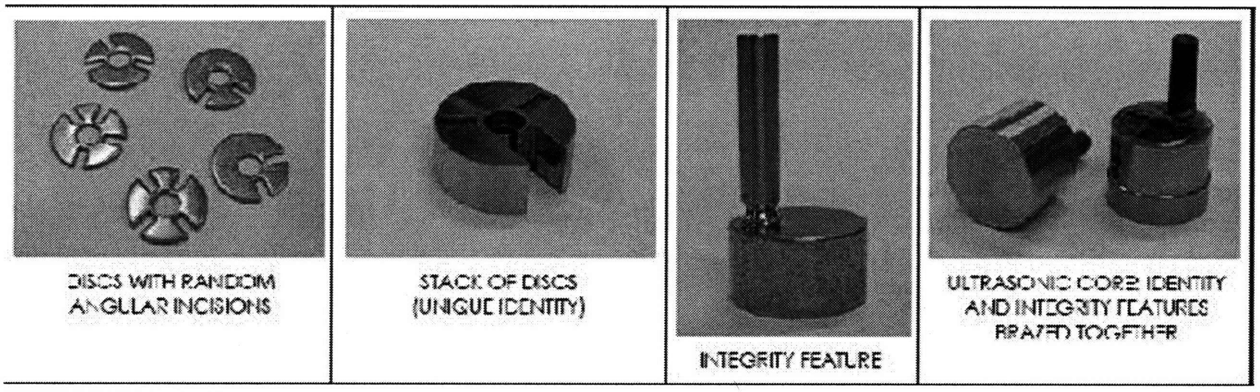
5.2.5 Sealing Systems

Another non-proliferation measure being taken from the CANDU safeguard system is the technology used to seal containers with nuclear material. It is important to securely seal the storage containers of nuclear fuel. Spent fuel assemblies may be transported great distances from the PRISM plant to the fuel cycle facility and diversion must be detected during this part of the fuel cycle as well as accounting for the waste. There are several sealing systems used and their use depends on where the nuclear material is stored. The current sealing system used at CANDU reactors to store spent fuel is the Atomic Energy of Canada Limited Random Coil (ARC). The seal is tamper-indicating. A new technology (ultrasonic sealing) has also been developed by the Seals and Identification Laboratory (SILab) which are designed to replace the ARC seal and still meet IAEA non-proliferation standards.

The CANDU reactors currently store spent fuel on-site and use ARC seals to close the storage casks. The seals are tamper indicating seals which work by having leaving a physical mark on the seal if someone tries to gain unauthorized access. (12) The seals are IAEA approved and inspected regularly while the spent fuel is stored and this insures the spent fuel bundles have not been diverted.

The new technology designed to replace the ARC seals is ultrasonic sealing and this technology can be implemented into the PRISM safeguard system. SILab develops technologies used for sealing and indentifying nuclear materials and they have developed ultrasonic sealing to replace the current ARC seals because of the advantages the new technology holds over what is currently being used.

The ultrasonic seal is used like any other seal when it is used to close a container such as a storage or transport cask. "The internal structure comprises a random identity and a frangible element … which breaks when an attempt is made to remove the seals." (13) The system uses a reading device, made of a transducer, which generates an ultrasonic signal and then reads the reflected signal. The reader rotates above the seal and records the signal from the seal over a complete rotation. The core of the seal is a cylinder which contains the "unique identity" of the seal and the frangible feature which breaks if opened. Figure 5.4 shows the core of the seal and the indentifying feature. The thin metal rod (shown in the third picture) breaks if a force is applied to the seal.



DISCS WITH RANDOM ANGULAR INCISIONS

STACK OF DISCS (UNIQUE IDENTITY)

INTEGRITY FEATURE

ULTRASONIC CORE IDENTITY AND INTEGRITY FEATURES BRAZED TOGETHER

Figure 5.4 Seal Core and Tamper Indicating Feature (16)

The reading device and interpreted signal is shown in Figure 5.5. The sound is given off by the transducer and reflected back when there is a discontinuity in the material. The wave signal is turned into an electronic signal and analyzed. The intensity of the signal is recorded as the reader rotates around the seal. The signal of the seal of when it is initially welded in is compared to the signal during inspection. Discrepancies in intensity will show if a seal is broken or not as shown in Figure 5.6. The highlighted area shows a change in the signal but the variation would have to be analyzed to determine if the seal is broken.

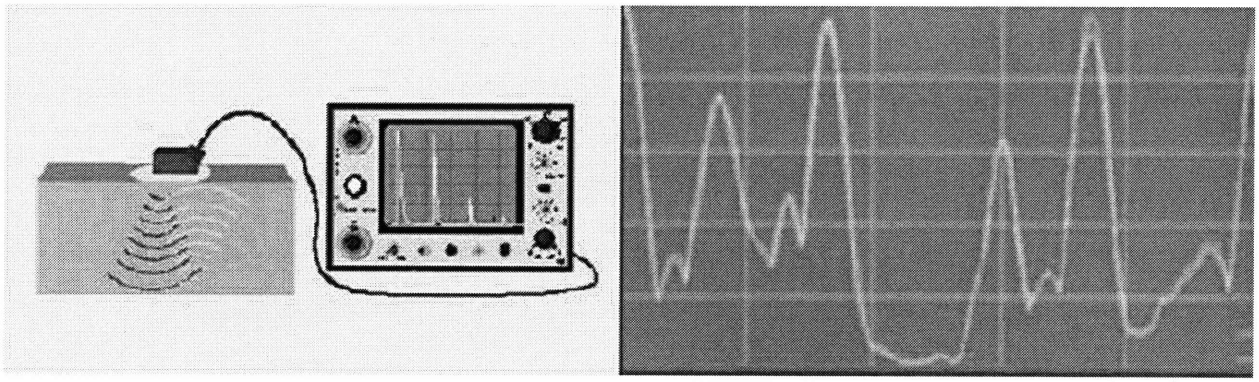


Figure 5.5 Reading Device (16)

The ultrasonic sealing system also has a few advantages over the current ARC sealing system. The ultrasonic seals are resistant to radiation damage and can last decades. Another advantage is the authenticity and status of the seal is immediately available to an inspector.

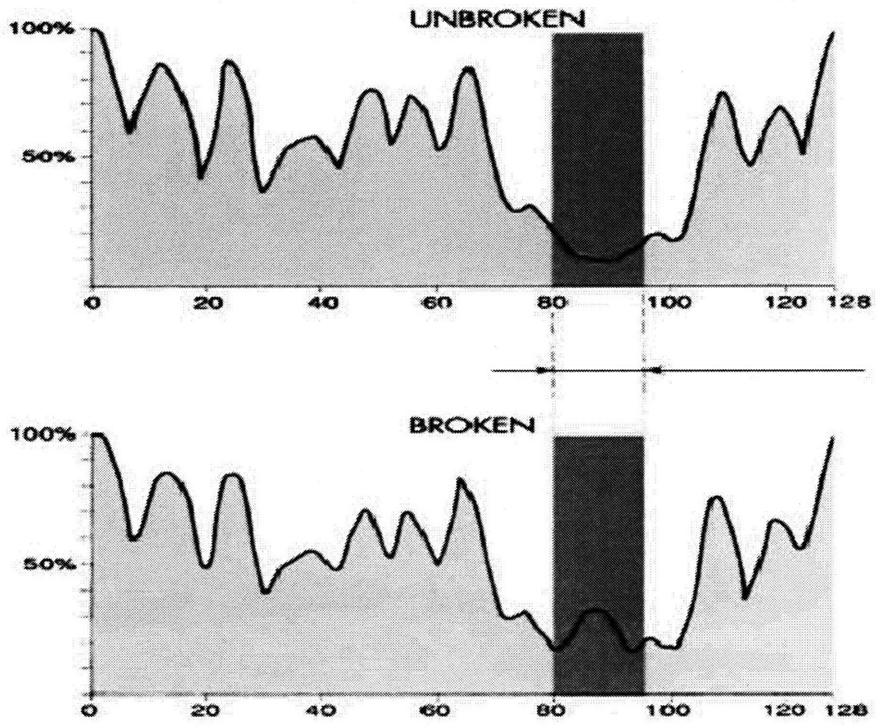


Figure 5.6 Broken Seal Signal Comparison

The PRISM plant would benefit from using these seals because of their ease of use. Waste stored at the fuel cycle facility can be monitored by camera, radiation detectors and also be sealed using the ultrasonic seals. In addition to the ultrasonic sealing of storage containers, electronic seals can be used as an alternative. Figure 5.7 shows a simple electronic seal. The IAEA has been pushing the development of new sealing technologies for the past six years. (15) The electronic seal works by having a sealing wire through the seal of a container or cask. If the wire will break the circuit if the container is opened and this is shown on the seal reader. An antenna can also be part of the system so that a signal can be sent immediately to the appropriate personnel at the security center of the PRISM plant and the IAEA. This sealing system can be used in order to seal more short term enclosures such as the transfer cask that carries spent fuel and fresh fuel, to and from the fuel cycle facility.

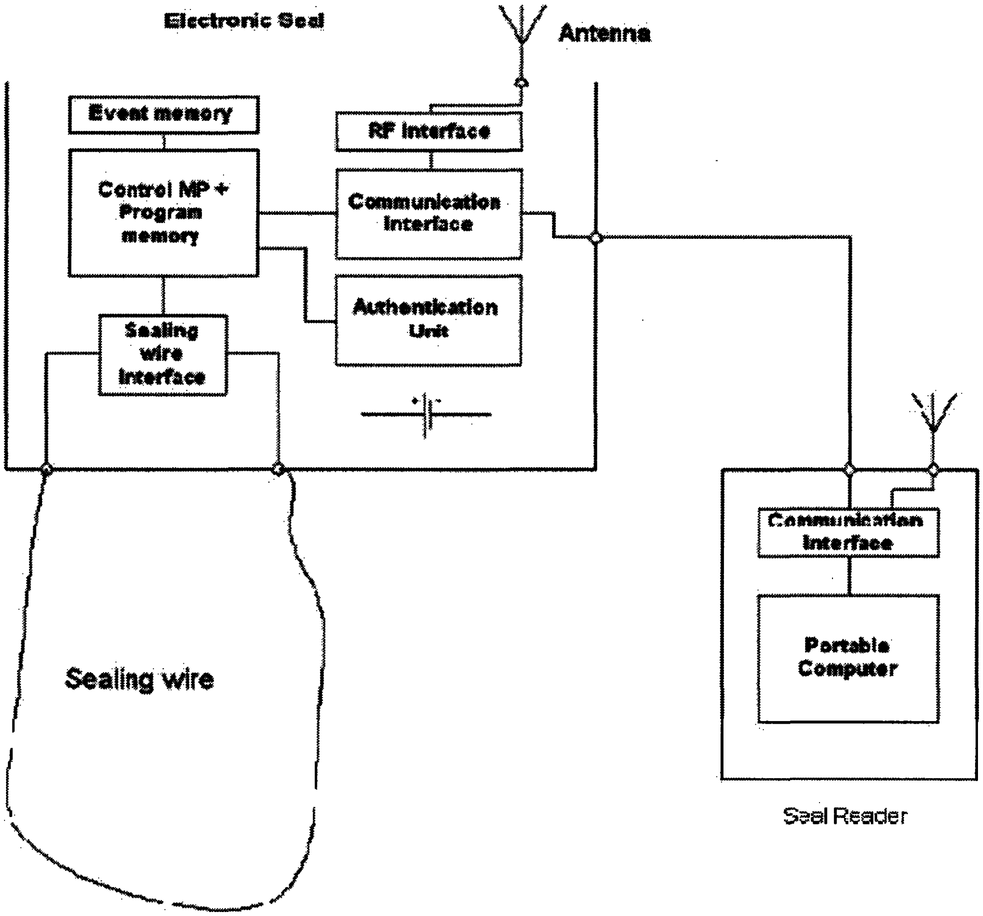


Figure 5.7 Electronic Seal (17)

5.2.6 Radio Frequency Identification Tags

Radio Frequency Identification (RFID) tags have been used in a variety of applications to keep track of different items. Their most common and familiar use is in supermarkets and department stores for the tracking of inventory. The tracking and verification of fuel in the PRISM plant and outside of it can be done using the RFID tags in a very similar manner.

The RFID tags consist of two parts. The first is the integrated circuit which contains all the information concerning the object that is tagged. The second is an antenna that is used to transmit information from the circuit to the reader using radio waves. There are passive and active RFID tags. The passive tags do not contain a power supply and instead are powered up and transmit a signal when a reader is close by and the radio waves of the reader induce a current in the circuit. The tag can then transmit a signal to the reader. Active tags are those which have a power supply, such as a battery, on board and can transmit a signal continuously to the reader. The tags some limitations which must be addressed such as lack of resistance to radiation and battery life under normal use. However, the research done by the IAEA is seeking to remedy or reduce the impact of these drawbacks.

The RFID tags would be used to track fuel assemblies throughout their entire movement in the PRISM plant and the Fuel Cycle Facility. The fuel is put into temporary storage for one year and after this time, the assemblies would be tagged with and RFID tag, which would contain necessary information to verify the fuel. The tagging would occur right before the fuel is loaded into a transfer cask. Information such as date of loading into the cask, the date it was discharged, and an identification mark such as a serial number would all be in the tag. The tags would help with quick identification and verification when the fuel is unloaded. This prevents dummy fuel assemblies from entering the fuel cycle and going unnoticed. The tags themselves will have their own tamper indicating sealing system designed specifically for the RFID tags. Figure 5.8 shows an example of a RFID tag which would be attached to a cask or fuel assembly while Figure 5.9 shows an example of a seal used to prevent tampering. The seal would be similar to that of an electronic seal.

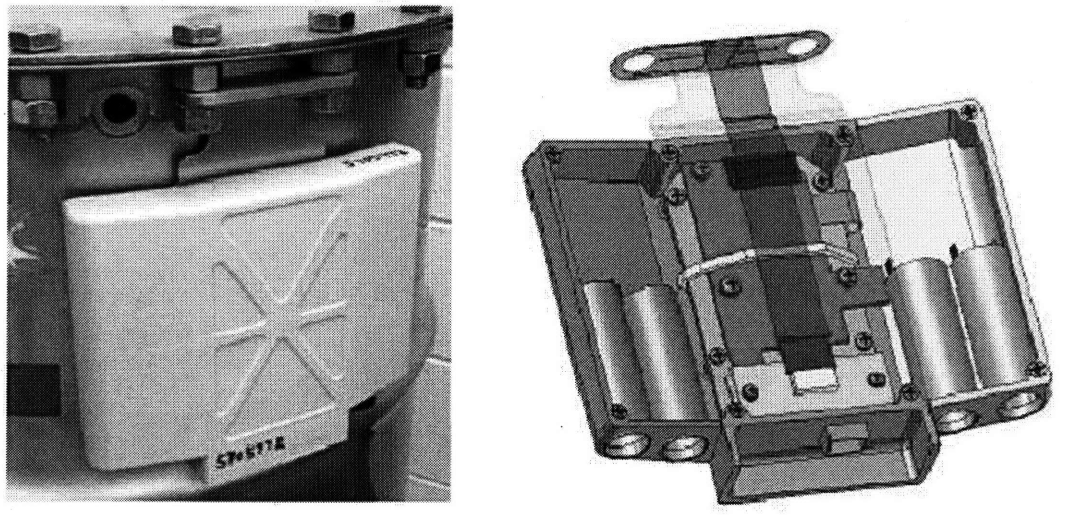


Figure 5.8 RFID Tag (18)

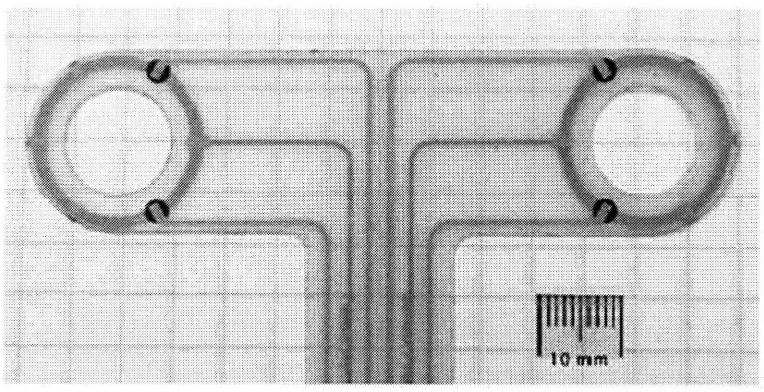


Figure 5.9 RFID Seal (18)

There is current testing being done on the use of RFID tags on containment drums which are used to transport fissile and radioactive materials. (16) The seals can be large or small and passive or active. Passive seals can be used for fuel assemblies so that the attached seal can be small and quickly applied. The larger, active seals would be used for the tracking of more permanent enclosures such as waste casks and would have battery packs that would allow for longer distance monitoring by an IAEA inspector.

5.2.7 Closed Circuit Television System

A standard feature of any safeguard system is video monitoring. The CANDU reactors use Closed Circuit Television (CCTV) to monitor all areas of the facility. Each PRISM plant would have to be surveyed to determine the appropriate locations of cameras around the facility. The video feed must be able to see every part of the facility and track the movement of all nuclear materials. Any part of the facility where seals and radiation monitors can be used would not require a camera. The CCTV system monitors any unauthorized movement of fuel throughout the plant. This is especially important for monitoring the storage of fuel in the reactor building and insuring that unauthorized personnel do not attempt to move fuel.

The cameras would be linked to the security center where personnel would monitor them at all times. Most CCTV systems at nuclear facilities still use tape and film but new digital systems are starting to replace the aging systems. Cameras such as the Digital Single Camera Optical Surveillance System (DSOS) are being installed at plants like CANDU and are IAEA approved. (10) The video would be stored on hard drives located at the PRISM plant and would last longer and be more secure than traditional tape and film.

5.2.8 Weight Scales

A new feature being added to the PRISM safeguard system is the use of weight scales for monitoring the presence of fuel and the verification of personnel entering the PRISM plant. The scale would be used at any point in the fuel's movement where the fuel becomes stationary and stored for an extended period of time, specifically the storage area in the reactor building and the fresh fuel storage. The weight of the entire load would be monitored by the security center. If a change is detected, it would have to be verified by the security personnel and if it is not, an alarm would sound. With the assemblies packed together, it prevents a diverter from removing a fuel assembly or pin without notice. They would also not be able to replace the fuel with a dummy element because if the weight of the entire load changes, either by increasing or decreasing a certain unauthorized amount, the alarm would sound.

The weight of personnel would also be monitored as they enter and exit the facility as described in Section 5.2.3. In much the same way, the person entering would have their weight monitored to insure no nuclear material is carried by the person.

5.2.9 Isotope Verification: Nuclear Resonance Fluorescence

Another new component to the safeguard system is a new technology that can identify isotopes present in a large enclosure such as a shipping container or for the purposes or the PRISM plant, a transport cask. It may eventually be used to replace the Spent Fuel Bundle Counter. The Nuclear Resonance Fluorescence (NRF) process is shown in Figure 5.10. The first step is the production of high energy electrons (8 MeV) which are scattered to produce Bremstrahlung radiation. The Bremstrahlung photons are then collimated and directed toward the container. The photons will excite the nucleus of the atoms in the container. When the nucleus comes down to a lower excited state or the ground state, it releases a photon with an energy specific to the nucleus. Detectors are set up directly in front of the container and to angles to cover backscattering. (17)

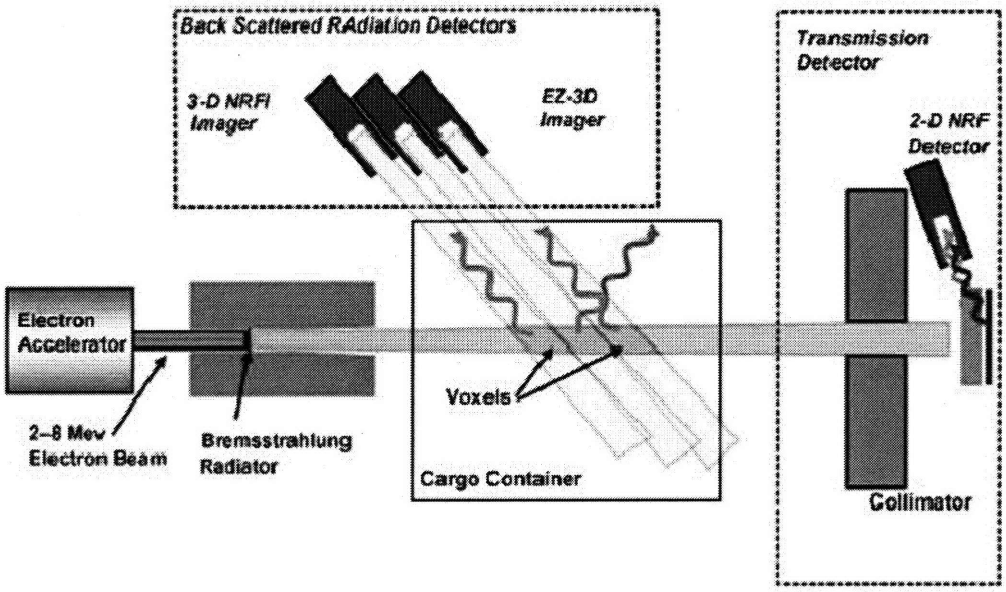


Figure 5.10 NRF Process

An example of the detected photons from the excited nuclei is given in Figure 5.11. Each nucleus has it own excitation energy which allows one to identify the specific isotope found in the scanned container. This NRF scanning would be implemented in a permanent location such as the storage area in the reactor building. This would verify the fuel assemblies and their contents. This would make identifying U-235, U-238 and Pu-239 in the assemblies possible and verify that what is being loaded into the transfer cask from the storage area is the fuel. If a dummy assembly or fuel pin is present, then the material used to make the dummy element would show up on the spectrum. This would be because the diverter would not use the same technology to make the dummy pin or the dummy element would only have the same weight and look of a pin and would not contain Plutonium or Uranium.

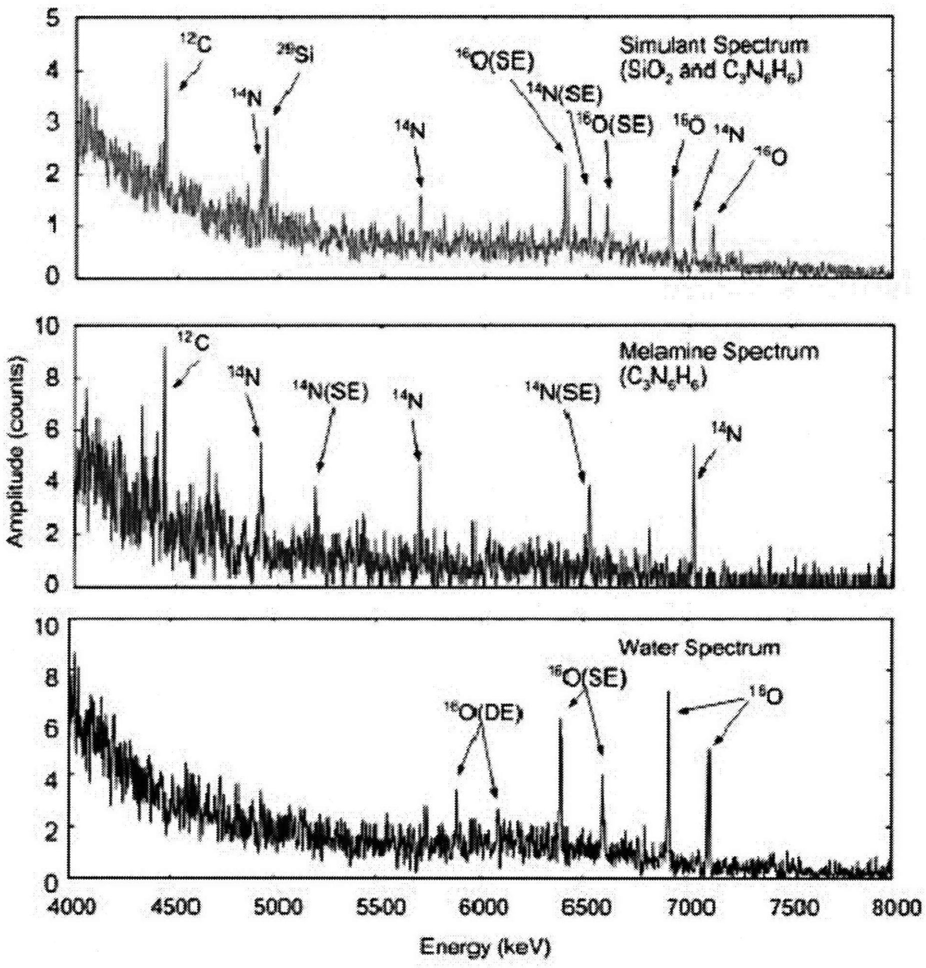


Figure 5.11 NRF Spectra (19)

5.2.10 Satellite Surveillance

This component would depend on the infrastructure of the host state and if it is willing to use it for the purpose of monitoring fuel during its transportation. Currently, the European Space Agency is the only known entity making an effort to use satellites to monitor nuclear material movement. They are doing this in cooperation with the IAEA. (19)

5.3 Addressing Diversion Scenarios

The dummy element diversion scenario is addressed through the verification of the fuel using the CANDU's SFBC or the NRF technology. The fuel has to be verified before it leaves the facility and after it enters it. RFID tags also allow for verification of all fuel assemblies. However, the removal of a pin from the storage rack would be detected by the weight scale and so a dummy element would do the diverter no good if they cannot get an assembly out in the first place. The portal monitors would also prevent the diverter from leaving with the pin or entering with the dummy element if the safeguards in the reactor building fail.

6. Conclusion

6.1 System Application

The safeguard system for the PRISM power plant is based on a constantly changing design. But this proves to be an advantage for the SFR project as this safeguard system could easily be modified to be used if a different reactor is used.

The CANDU safeguard system proved to be a good base for the development of the PRISM system. The components were not only taken from the CANDU system, but alternatives to some components, such as the NRF identification, were included if possible.

Diversion scenarios were developed in order to help with the thought process of developing the safeguard system. The scenarios provided insight into what the diverter would hope to achieve and what the most likely way to achieve this end would be. The addition of GPS tracking and weight scales is due to addressing the diversion scenarios with a simple yet effective technology.

6.2 Work to be Done

Work to be done includes doing cost analysis and verifying that technology not used for safeguards is approved by the IAEA. The purpose of the SFR project is to create a power plant system that is cost effective. The safeguard system must not raise the cost of the plant. However, an analysis of the cost versus the advantage of having more safeguards in place to mitigate negative feelings against nuclear power must be done.

New technology such as the NRF identification must also be tested for use in a power plant environment and to insure that the IAEA approves this component. IAEA approval is important, especially for a host state which has not yet started a nuclear power program and would need international help and approval to do so.

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