SAFEGUARDS ISSUES FOR CHERNOBYL UNIT 4 ("SHELTER")

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ABSTRACT

The IAEA and Ukraine have been discussing the issue of safeguarding nuclear material at Chernobyl Unit 4 (also referred to as the Shelter) for several years. After Ukraine's accession to the NPT, an updated Initial Inventory Declaration for Chernobyl Unit 4 was submitted to the International Atomic Energy Agency (IAEA) in 1998. This declaration includes fresh fuel, core fuel, and spent fuel. It takes into account nuclear production and loss with estimated plutonium content and uranium burn up, respectively, as of the date of the accident. It does not take into account any losses of the nuclear material in the Shelter since the time of the accident and the whereabouts of that material.

Brookhaven National Laboratory (BNL), Pacific Northwest National Laboratory, Sonalysts, and State Russian Scientific Center Institute of Physics and Power Engineering (IPPE) have worked with the IAEA and Ukraine to define the safeguards and security issues. They are reviewing the conditions of the fuel containing material, the present facility status, and plans for the new Shelter. This team is investigating the status and whereabouts of fuel containing materials in the Shelter and vicinity and explaining safeguards and security challenges. This paper will present the basic challenges of fuel characterization and safeguards and security at Chernobyl Unit 4.

Keywords: Chernobyl, IAEA Safeguards, Fuel Containing Materials Characterization

INTRODUCTION TO SAFEGUARDS ISSUES IN SHELTER

The IAEA and Ukraine have been discussing the issue of safeguarding nuclear material at Chernobyl Unit 4 for several years. After ratification of the NPT, Ukraine submitted an updated Initial Inventory Declaration for Chernobyl Unit 4 to the IAEA in 1998. This declaration includes fresh fuel, core fuel, and spent fuel. It took into account nuclear production and loss with estimated plutonium content and uranium burn up, respectively, as of the date of the accident. It does not take into account any losses of the nuclear material in the Shelter since the time of the accident and the whereabouts of that material. In attempting to craft a safeguards approach for the Shelter, BNL, PNNL, Sonalysts, and IPPE, as consultants to the IAEA, in cooperation with state authorities and operators in Ukraine are working on solutions to difficult safeguards issues unique to the Chernobyl Unit 4 environment.

This consulting team has identified four main problems. The first and foremost problem is analyzing a facility that was catastrophically destroyed and does not fit the IAEA facility categories for a reactor or for a storage facility. This is a unique facility and safeguards criteria specific to the situation at Chernobyl will need to be created. The second major problem is that

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uncertainties about the state of the nuclear material, the location of the nuclear material, and the amounts of the nuclear material exist1,2,3. Fuel Containing Material (FCM) characterization analysis will look into these first two problems and help to categorize the facility and its fuel materials. The third major problem is that analyzing containment and surveillance of nuclear material is problematic because of the state of and deterioration of the present Shelter that was constructed quickly in 1986 under severe conditions[3,4]. A traditional nuclear power plant would have fairly easy to identify access routes for the removal of core and spent fuel casks. This is not the case for the Shelter where there are more access routes and the nuclear material is now broken up into small fragments that can be removed in small containers. The fourth major problem is with the design of the new Shelter, the New Safe Confinement (NSC), which is part of the Shelter Implementation Project (SIP). The huge NSC will cover the old Shelter and have cranes installed from its roof capable of removing the old deteriorating old Shelter roof which would give access to the damaged Unit 4 reactor hall and spent fuel ponds[4]. These cranes could be used to clear up the rubble in this region and gain access to the 129 fairly intact spent fuel assemblies containing low-enriched uranium (LEU) and plutonium and 48 somewhat damaged fresh fuel assemblies containing LEU. The spent fuel may still be suitable for packaging in a cask for removal and eventual reprocessing. The LEU from the fresh fuel could be used to feed an enrichment plant or plutonium production reactor. Hence, one must worry about the capabilities of the NSC to remove the material that is most desirable from a diverter's viewpoint in the Shelter. The safeguards approach will dwell heavily on these last two problem areas. The consulting team has at this stage in the project studied these crucial challenges and described some preliminary paths for dealing with them.

STATE OF CHERNOBYL UNIT 4

Chernobyl Unit 4, as shown in Figure 1, is a heterogeneous, thermal neutron, graphite-moderated, channel-type boiling-water nuclear reactor with on-line refueling. It is one of the four completed RBMK-1000 plants at the Chernobyl Nuclear Power Plant (ChNPP). It is a second generation RBMK-1000 with 1000MW electrical output (3140 MWt) completed in 1983. It allowed up to 1661 UO_2 core fuel assemblies (FA) with 1.8% to 2.4% U-235 enrichment to be inserted into the core barrel. At the time of the accident on April 26, 1986 it held 1659 fuel assemblies in the core, 48 fresh fuel assemblies in the reactor Central Hall (CH) in preparation for loading, and 129 spent fuel elements in the South Spent Fuel Pond (SSFP)[1,2,3,5]. There were 36 other fresh fuel elements in the ChNPP Unit 4 fresh fuel storage area which were slightly damaged during the accident[5]. ChNPP moved these 36 assemblies to the damaged fresh fuel storage for the Units 1, 2, and 3 where they are under IAEA safeguards[5].

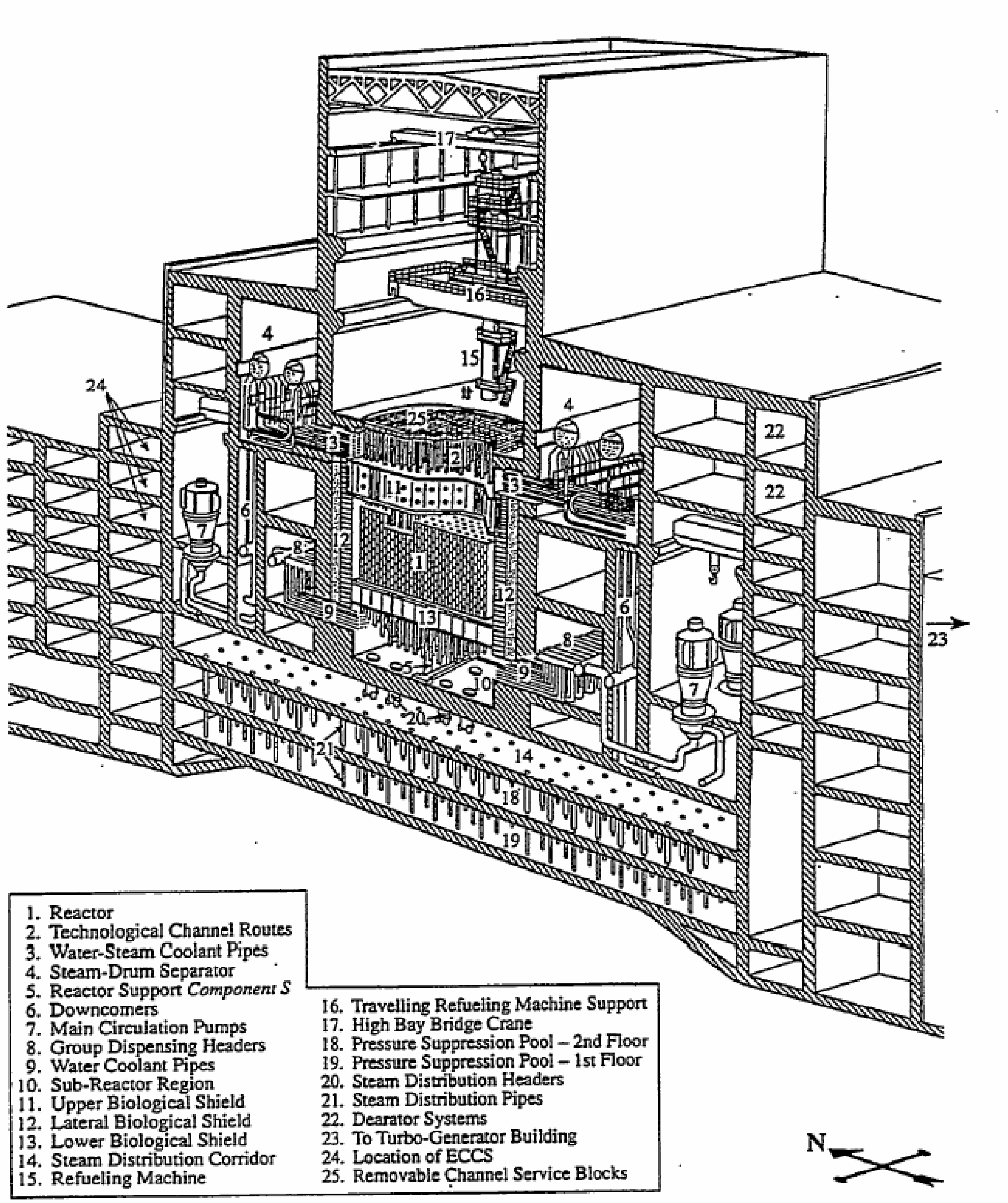

Figure 1: Intact Chernobyl Unit 4 Cross-Section[6]

During the course of the accident the reactor compartment integrity was breached and the core entirely destroyed (Figure 2). The reactor hall sustained severe damage. Significant amounts of nuclear material were ejected from the reactor. Researchers have estimated up to 3±1.5% of the fuel was ejected. It is believed that ~96% of the nuclear core material is still within the Shelter[7]. There are estimates of the fuel compositions at the time of the accident in Table 1 taken from available open literature[1,2,3,5,7,8]. The aim of Fuel Characterization of Materials (FCM) task is to progress from this starting point of Table 1 to estimating the location and composition of the remaining Shelter materials. For safeguards this means getting an estimate of material to be safeguarded and an estimate of the material released from the facility that could be claimed as a loss.

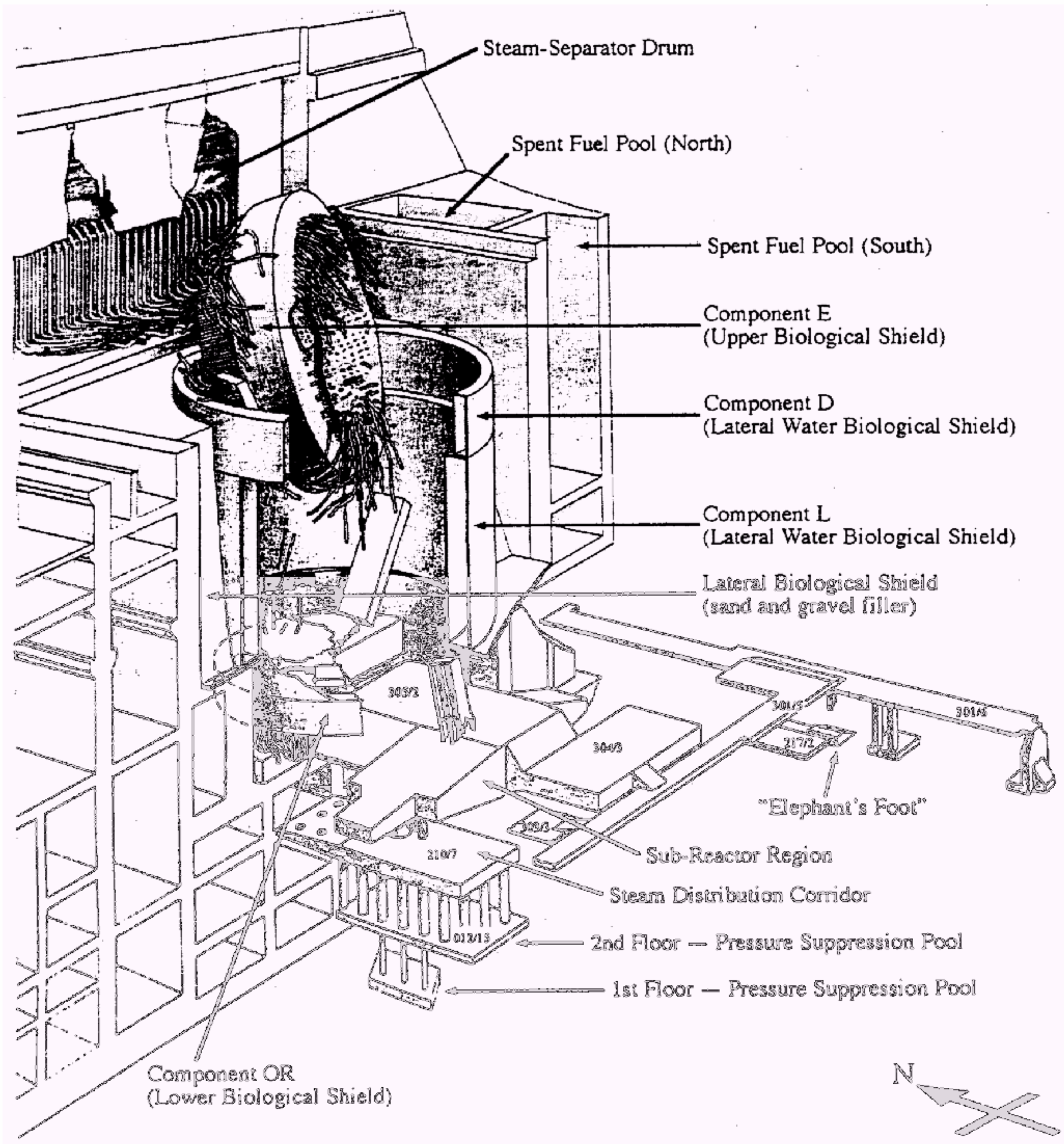

Figure 2: Post-Accident Chernobyl Unit 4 Cross-Section with LFCM Pathways[3]

Nuclear Fuel Location in ChNPP4	Number of FAs	Single FA Weight, kg U	Total Weight of U, kg U	Weight U-235, kg U-235	Weight Pu, g Pu
Core	1659	114.7	190287	1902	761
SSFP	129	114.7	14796	148	59
CH (Fresh FA Prep Area)	48	114.7	5506	110	0
TOTAL	**1836**		**210589**	**2160**	**820**

Table 1: Nuclear Materials in Chernobyl Unit 4 with State at the Time of Accident

The material that was ejected from the shelter was not only in small particulate form that was totally lost but also in larger core fragments that included graphite from the fuel channels. These fragments landed up to 1600m from the ChNPP Unit 4. These materials will also be considered as lost for safeguards purposes if they are not located. However, during excavation for the NSC some of the core fragments may be detected by radiation sensors and need to be disposed of and accounted for by the IAEA. However, the main materials safeguard concern is the fuel that still resides in the Shelter.

FUEL CONTAINING MATERIALS SAFEGUARDS CONCERNS

The major concern of FCM is to analyze the state of the materials residing in the Shelter. Several authors have assembled the available data to create descriptions of the amount and location of the material in the Shelter[1,2,3,5,7,8]. High radiation fields inhibited a thorough investigation of the Shelter. Furthermore, concrete used to construct the Shelter and gravel used to cover the immediate contaminated environs of ChNPP Unit 4 buried significant amounts of FCM (Figure 3). Because of these hardships, researchers extracted only a limited number of samples from all of the FCM types and areas of the reactor. Research teams from the Soviet Union, Russia, and Ukraine analyzing the samples and other data from ChNPP Unit 4 had differing ideas on the FCM characterization in the Shelter. Their results also contained large uncertainties. Because of the enormity of the task, hazards in entering the Shelter, and cost of categorizing the FCM, it will be years before, if ever, researchers can create a definitive material accountancy in the Shelter. There was 190.3 metric tonnes of uranium in the core at the time of the accident. Today various researchers believe that the Shelter contains between 172-180 metric tonnes of uranium from the core with large uncertainties of up to ±30 metric tonnes. This FCM has uranium of approximately 1% U-235 enrichment in various physical and chemical forms. The Shelter also contains 691±112 kg plutonium from the core. An additional 14.8 metric tonnes and 5.5 metric tonnes of uranium from 129 spent fuel and 48 fresh fuel assemblies, respectively, are still in the Shelter. The material ejected from the reactor vessel is estimated to be 6±3 metric tonnes of uranium of ~1% U-235 enrichment and about 23±11 kg of plutonium[1,2,3,5,7,8].

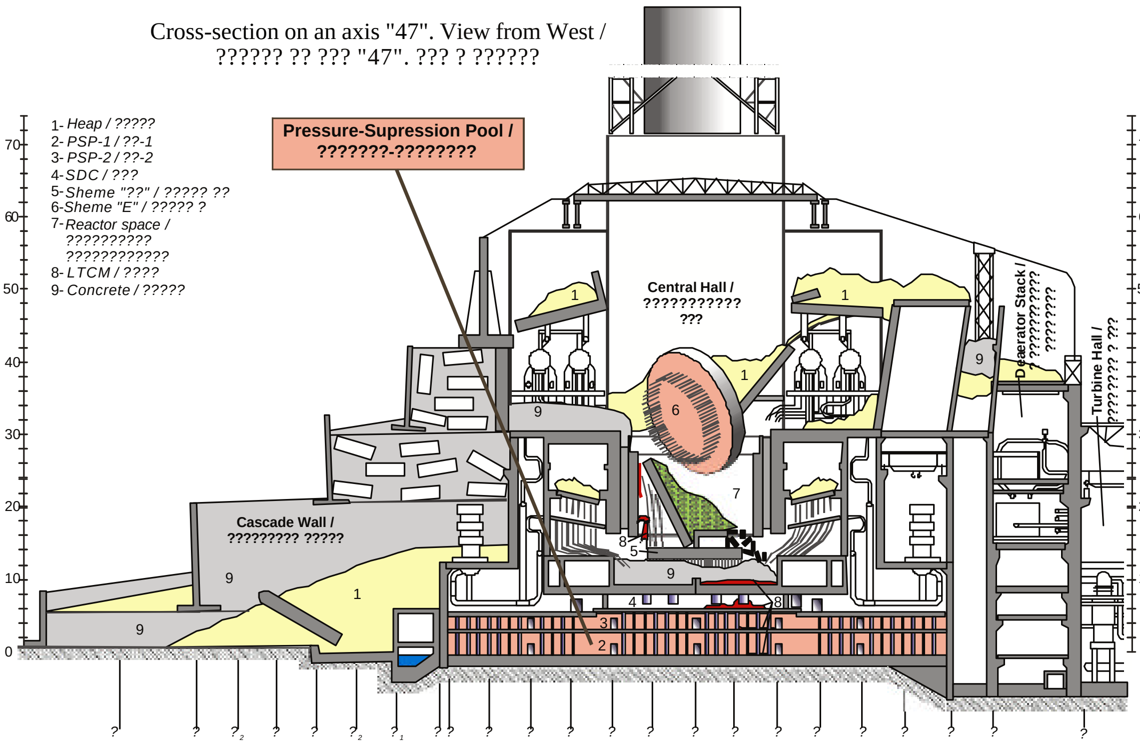

Figure 3: Chernobyl Unit 4 Shelter Cross-Section[1]

The uncertainties in nuclear material accountancy create a significant problem for IAEA safeguards. Traditionally, IAEA safeguards at reactors accounts for material in an item form in distinct integral packages. Bulk materials are traditionally handled mostly in reprocessing, enrichment, conversion, and fuel fabrication facilities. However, here we have the items, fuel assemblies, destroyed and spread about the reactor and beyond. Traditional approaches to accountancy can not accommodate ChNPP Unit 4 fuel. Furthermore, as stated previously, the ChNPP Unit 4 does not fit into a traditional IAEA facility category as a reactor or a storage facility. It is unique.

The state of the core fuel is also a problem for safeguards. The core fuel is in the four following FCM forms: core fragments, dispersed fuel, the so-called lava-like FCM (LFCM), and contaminated water containing dissolved uranium and plutonium. Core fragments from the vertical RMBK channels exist because not all fuel melted in the accident especially in the periphery of the core. The fuel bundles were in the graphite columns. Some of the fragments are still entwined with their graphite channel. These fragments emit high levels of radiation with Cs^{137} gamma radiation. It can be difficult to distinguish the core fuel fragments from cesium laden graphite as the cesium fission fragments leached from the damaged fuel pins into the graphite[9]. Fuel fragments in the range from the millimeter to the centimeter scale are fairly intact. Dispersed fuel exists in a dust form in the hundreds of micron scale and is found in all rooms of the shelter presenting a radiation hazard to workers in the Shelter and to off-site civilians if the present Shelter's structural integrity should fail. The LFCM formed during the active phase of the accident as the core melted, interacted with structural materials, especially the lower biological shield, and flowed into the lower regions of the reactor building. These LFCMs are glass-like or pumice-like silicate substances that contain fuel and other materials of the reactor including metallic alloys. As time goes by, more dust is being created as LFCM degrades into a powder from the intense radiation fields. If this process accelerates, according to some researchers, a sudden degradation of the LFCM may occur with dust from the LFCM spreading in Shelter. The contaminated water containing dissolved uranium and plutonium dust is in the lower regions of the reactor, especially in the two-story suppression pool under the reactor that can be seen in Figure 1. This amount of material is very small and diluted. It should not be a real safeguards concern. Knowledge of the state and amounts of the core fuel would provide information needed to do some form of gross material accountancy and to stratify the material by different forms of FCM. If some or all of the FCM "has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards or has become practically unrecoverable" (Safeguards Policy Series Number 14 – 1994-09-09), the IAEA can terminate safeguards on the material meeting those criteria.

Hence, the task of safeguarding the Shelter FCM must acknowledge the uncertainties in the Shelter FCM data and attempt a unique approach to safeguards while attempting to incorporate present IAEA safeguards criteria and directives. The first step in safeguarding the Shelter material is to analyze the present best-estimates of the FCM to get an idea of the situation in the Shelter[1,2,3,5,7,8]. Open literature estimates of the ChNPP Unit 4 core FCM inventory should suffice to provide data for us to recommend a path forward for the IAEA to create material categories and criteria for the Shelter. Table 2 shows an estimate of the FCM inventory our team has created using some of the best data available to calculate the nuclear material inventory and material location. It is apparent that there is uncertainty in the material inventory. Table 3 illustrates how this can occur by showing how some rooms of the Shelter, as was shown in Figure 3, contain large amounts of concrete and debris complicating analysis of the material. Furthermore, the radiation fields in the Shelter around the LFCM in the lower regions of the reactor as well as in the reactor hall are high, ranging from 1 R/hr to 1000 R/hr. This will cause problems for the operator, as well as the IAEA, in getting additional destructive assay (DA) samples to define the material. The IAEA traditionally has the operator do the sampling under IAEA inspector observation to verify that the proper material has been sampled. The high radiation fields will make this difficult, if not impossible, to do at the Shelter. Traditional IAEA non-destructive assay (NDA) techniques will also be difficult to implement because of the problem of access and high radiation fields.

Strata	Description	Location		# of Items	U, Metric tonnes U	Total Uncertainty of U, Metric tonnes U	U Conc., Weight %	Avg. U Enrichment, Weight %	Calc. Pu , kg Pu	# FCM Samples Taken
A	Spent Fuel	505/3	South SF Pool	129	14.8		85	0.92	57	
B	Fresh Fuel	504/2	Whole - Central Hall	48	5.5		88.2	2	0	
C	Dispersed Fuel Outside of Shelter	Offsite	Offsite	NA	10			1	36	
D	Core Fragments Scattered after Explosion	914/2, etc…	Central Hall, Walls, Outside	NA	36			1	129	
E	Dispersed Fuel in Dust and Hot Particles	Unit 4 Wide	Unit 4 Wide	NA	1			1	4	
F	Dissolved materials in liquids	Lower Reactor	~20 rooms in Shelter	NA	0.1			1	0.4	
G	Fuel Containing Materials	012/7	Pool Bubbler 1	NA	1.5		9.8	1	5.4	10
		012/15	Pool Bubbler 2	NA	8		9.9	1	29	9
		217/2	Elephant's Foot	NA	2		4.6	1	7.2	27
		301/5	Main. Corridor	NA	3		4.5	1	11	13
		301/6	Main. Corridor	NA	3		3.7	1	11	9
		303/3	Main. Corridor	NA	0.2		3.7	1	0.8	17
		304/3	Main. Corridor	NA	14		4.4	1	51	33
		210/6	Steam Dist Corridor	NA	25		6.8	1	90.6	12
		210/7	Steam Dist Corridor	NA	11		9.8	1	40	20
		305/2	Sub-Reactor Premise	NA	75		10	1	272	56
TOTAL INTACT FA (A-B)				177	**20.3**				**57**	**NA**
TOTAL FCM IN SHELTER (D-G)				NA	**180**	**+/-30**			**651**	**206**
TOTAL MATERIAL ACCOUNTED FOR (A-G)				NA	**210**	**+/-33**			**744**	**206**

Table 2: FCM Nuclear Material Distribution in Chernobyl Unit 4 Shelter

Strata	Description	Location		FCM Material Type	Core Fragments	LFCM	Pumice	Metal	SUM	Graphite	“Fresh” concrete	Geometry\quantity	Access
A	Spent Fuel	505/3	South SF Pool		+	-	-	-	-	-	- ?	+	B
B	Fresh Fuel	504/2	Whole - Central Hall		+	+	-	-	?	+	+ P?	+ ?	BER
D	Core Fragments	914/2, etc…	Central Hall, Walls, Outside		+	?	?	-	?	+	- ?	?	BER
G	Fuel Containing Materials	012/7	Pool Bub. 1	Brown, pumice	-	+	+	+	+	-	+ P ?	+ ?	E
		012/15	Pool Bub. 2	Brown, pumice	-	+	+	+	+	-	+ P ?	+ ?	E
		217/2	Elephant's Ft.	Low Black	-	+	-	-	?	-	+ P ?	+ ?	E
		301/5	Main. Corr.	Low Black	-	+	-	-	?	-	+ P ?	+ ?	BE
		301/6	Main. Corr.	Low Black	-	+	-	-	?	-	+C ?	?	E
		303/3	Main. Corr.	Low Black	-	+	-	-	?	-	+ C	?	BE
		304/3	Main. Corr.	Low Black	-	+	-	-	?	-	- ?	+ ?	BE
		210/6	SDC	High Black	-	+	-	+	+	-	+ P ?	+ ?	BE
		210/7	SDC	High Black	-	+	-	+	+	-	+ P ?	+ ?	BE
		305/2	Sub-Reactor	Not Lava	+	+	-	+	+	+	+ P ?	?	BER

TABLE KEY:

FOR Core fragments, Lava (LFCM)**, Pumice** (pumice-like FCM)**, Metal** (melted and solidified metal)**, SUM** (contain uranium and trans-uranium elements),**Graphite** (reactor core graphite):
“+” – Available,
“-“ – Unavailable,
“?” – No defined for sure.
FOR “Fresh” concrete:
“+” – “Fresh” concrete available in premise,
“–“ – No “fresh” concrete in the premise
“C” – “Fresh” concrete covers FCM completely,
“P” – “Fresh” concrete covers FCM partially,
“? ” – FCM lying openly,
“?” – Availability of FCM under “fresh” concrete is not defined for sure.
FOR “Geometry\quantity” (FCM location, geometric sizes, and quantity):
“+” – Defined with sufficient level of reliability,
“-“ – Not defined,
“?” – Should be specified (data has discrepancies),
FOR “**Access**”:
“B” – Access via available boreholes is possible,
“E” – Premise (room) can be accessed by personnel,
“R” – Access is possible from above via available openings on the roof.

NOTE: SDC = Steam Distribution Corridor

Table 3: SF, FF, and FCM States in Chernobyl Unit 4 Shelter for Selected Strata

The material can be broken down into the subcategories or strata that the IAEA uses to categorize nuclear material in traditional facilities. In a normal light water reactor (LWR), one finds the material categorized as fresh fuel, core fuel, and spent fuel. In the Shelter there exists the spent fuel and fresh fuel described previously that is damaged but are still integral items. These we have called stratum A and stratum B, respectively. These items will be of the most concern for safeguards because of being relatively intact and having higher weight percents of uranium and plutonium than the FCM from the destroyed core. UO_2 pellets in the fresh fuel contain 88% uranium by weight percent. The UO_2 pellets in the spent fuel contain around 85% uranium and 0.4% plutonium by weight percent. Other materials such as the LFCM are only 4-10% uranium by weight percent and mixed with other materials. Some of the fresh fuel and the spent fuel pool covers are presently covered by debris and in high radiation fields. However, the NSC will have cranes attached to its roof that will be used to dismantle the old roof of the Shelter and other dangerously decaying parts of the Shelter to avoid a catastrophic collapse. These cranes could be used to access and divert the fresh fuel and spent fuel. The operator could bring in casks for the removal of the fuel. He could load the casks remotely from the crane and remove the casks from the shelter.

The stratum C, the dispersed fuel outside the reactor and the Shelter is a concern because of the chance that semi-intact fragments may be unearthed in the NSC excavation phase where 5m deep trenches will be dug for the NSC foundation. Plans must be made for the operator to tag and categorize these fragments for disposal diluted in high level waste. The stratum D, the core fragments scattered in the reactor, is of some concern because of the chance that semi-intact fragments may be removed during the Shelter improvements and NSC construction phases. Since the fuel fragments from these two strata can contain large chunks of graphite and would be strewn over the upper reactor compartments, on the Shelter site, and off-site, it is doubtful significant quantities of nuclear material can be obtained easily from these 2 strata. However, safeguards need to be applied in some manner to these strata.

Stratum E, the dispersed dust fuel in dust and hot particles, is too small to be easily collected in significant quantities. However, it is a radiation hazard and is growing all the time because of the deterioration and decay of the LFCM into dust. Vacuuming up the dust would be an option for a diversion but would be difficult. It may be more of a concern in the NSC where an air filtration system could collect the dust. Stratum F, the dissolved uranium and plutonium, can probably be terminated from safeguards because of the small amounts and being diluted in the puddles of water in the lower regions of the reactor that are in high radiation fields. Hence, diversion schemes for strata E and F are not very credible.

Stratum G, the LFCM, can be examined in some detail since samples have been taken of the LFCM and the operator does have knowledge, at least in a general sense, of the composition of the LFCM in different areas of the lower regions of the reactor. The high radiation fields, debris clogged passages, and diluted nature of the LFCM (4-10% uranium) make it unattractive for diversion. However, the LFCM uranium is not dilute enough to meet termination of safeguards criteria under IAEA guidelines (Safeguards Policy Series Number 14 – 1994-09-09) for wastes from reprocessing and other parts of the fuel cycle. The uranium concentrations in the LFCM range from 20 to 50 times the maximum concentration guidelines for termination under these guidelines.

POSSIBLE SAFEGUARDS APPROACH OPTIONS FOR SHELTER

After analyzing the situation at the Shelter, the development of a safeguards approach focused on integrating the physical protection with the safeguards containment and surveillance to create a boundary around the Shelter and monitor any removals of the material across that boundary. Traditional IAEA safeguards focusing on the material accountancy of the material would be replaced by a focus on containment and surveillance (C/S) systems. Accountancy would become a major concern of the IAEA when and if the operator decides in the future to dispose of the FCM material making it necessary to account for and monitor FCM removals. The IAEA would depend upon operator declarations, official publications, and open source articles to estimate the material inventory in a manner similar to the approach described in the previous section. Design Information Verification (DIV) could be done for the present Shelter with each modification to the Shelter and the new NSC to be verified by the IAEA as each change is made on a timely basis.

The consulting team foresees a C/S system as the main means of implementing safeguards. It should use a dual C/S mode defined as the use of two independent C/S systems which are functionally independent and are not subject to a common tampering or failure mode. This would involve two totally different independent surveillance systems using different techniques, a sealing system plus surveillance, and/or a radiation monitor coupled with surveillance and sealing systems. The goal would be to monitor the access routes to the Shelter. The cranes to be installed in the NSC would have to be covered by surveillance to monitor any attempt to divert fresh fuel, spent fuel, or core fragments strewn over the reactor hall. At present there is access into the Shelter itself from the exterior and through ChNPP Unit 3. Monitoring access into the Shelter itself would be the best solution.

The safeguards approach should cover, as stated in the previous section, the question of discoveries of scattered fuel fragments outside the reactor. Criteria will have to address the procedures for the operator and IAEA for handling and accounting for this material.

The verification of the inventory will have to be done in nontraditional ways as discussed in the previous section. The samples that the Interdisciplinary Scientific and Technical Centre "Shelter" (ISTC) already have may be sampled by the IAEA for DA to get some official and independent verification of the type of material in the Shelter[9]. If the operator has a future campaign of new sample taking, the IAEA should work with the operator to verify their sample taking and take a share of the new samples for analysis by the IAEA. As stated above, if conditions change in the Shelter and FCM is removed in the future, the IAEA should work with the operator to get verification of the amounts removed and their storage and eventual disposal.

CONCLUSIONS

The ChNPP Unit 4 presents enormous challenges to the IAEA for safeguards implementation. In this paper we have attempted to focus on the basic areas of concern for safeguards of FCM and safeguards approach. We feel that the analysis of the best of the research studies of FCM should provide the IAEA with sufficient basis to create criteria and stratification of material for the Shelter. Since the inventory can not be verified by traditional methods, an estimate of the inventory will have to suffice. At present, it would be best to not terminate safeguards on the material but monitor it under C/S until such times in the future that may be anywhere from 10-100 years from the present when the material may be removed. The IAEA should focus its efforts at the Shelter on C/S techniques using cameras, radiation monitors, and sealing to have assurance that the material in the Shelter is not removed.

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