GREENPEACE

MOX FUEL PRODUCTION STANDARDS, QUALITY CONTROL AND NUCLEAR POWER PLANT SAFETY IMPLICATIONS FOR BOILING WATER REACTORS AT OSKARSHAMN, SWEDEN

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"… confidence in BNFL has been destroyed." Takashi Fukaya, Japan's Minister of International Trade and Industry, December 1999

"The nation's energy policy as a whole, including the nuclear fuel cycle policy, must undergo a total review in order to gain the approval and understanding of the people." Governor of Fukushima Prefecture, Japan, February 8th 2001 (commenting in relation to the use of Belgonucleaire MOX fuel in a Japanese reactor in July this year)

"SKI judges that both manufacturers of MOX fuel have a large experience manufacturing such fuel and that production can occur in a safe fashion, and have high quality." Statens Kärnkraftinspektion, SKI, submission to Swedish Environment Ministry in support of OKG application to use MOX fuel, June 30th 1999.

PREAMBLE

In November 1998 Swedish utility OKG submitted an application to the Swedish nuclear regulator Statens Kärnkraftinspektion, (SKI) for a license to import and use plutonium Mixed Oxide fuel, or MOX, in one of its Boiling Water Reactors (BWRs) at Oskarshamn. The application proposes that plutonium reprocessed at British Nuclear Fuels (BNFL) Sellafield site from OKG spent fuel would be manufactured into MOX at either BNFL's new Sellafield MOX Plant (SMP) or the Belgonucleaire MOX plant P0 at Dessel, Belgium. In June 1999 SKI submitted to the Swedish government its opinion of the application, which recommended that OKG proposal was justified on safety grounds and should be accepted.

Since SKI completed its review of OKG's application a number of facts with significant implications for the safety of MOX fuel have been revealed. These include revelations of falsification of quality control documentation at European MOX plants, problems inherent in MOX manufacture, as well as new data research on the risks of using MOX fuel in Light Water Reactors (LWR) and BWR's in particular.

Other information concerning risks associated with MOX use and problems related to MOX manufacture, although available at the time of SKI's submission of its opinion to the Swedish government, did not seem to have been considered in the forming of the opinion. Neither did SKI provide this information to the Swedish government as background.

The purpose of this paper is to summarize the additional and recently disclosed information for the Swedish government, in order to make sure that it is able to make a decision on OKG's MOX plans based upon an understanding of the reality of MOX production in Europe.

INTRODUCTION

During the last 18 months, evidence has emerged that the problems which led to the scandal involving the falsification of quality control (QC) data for plutonium Mixed Oxide (MOX) fuel by British Nuclear Fuels (BNFL) delivered to Japan, were not an isolated incident. Evidence has emerged that the problems of MOX production are inherent, that it also concerns the new Sellafield MOX Plant, (SMP), as well as other European MOX facilities.

As a direct consequence of the BNFL MOX scandal, investigations began during early 2000 into production standards and quality control at Belgonucleaire's P0 plant in Belgium and Cogema's Melox and Cadarache (CfCa) facilities in France. Doubts over quality control and production standards now apply to all of these facilities. Due to on-going developments in Japan, it is the Belgonucleaire facility that has come under most scrutiny. This facility supplied MOX fuel to Japan at the same time as the BNFL shipment in 1999. Although the MOX fuel delivered, consisting of 32 assemblies, was due to be loaded in after arrival in September 1999, to date it remains stored at the reactor site, Fukushima-1-3.

During last year evidence also emerged of the falsification of quality control at Belgonucleaire. This has led to a legal investigation in Japan, which depending on the outcome could lead ultimately to the rejection of the MOX fuel by its owner, Tokyo Electric Power Company. Evidence that MOX fuel produced by Belgonucleaire and Cogema is of an even lower quality than that produced by BNFL, together with evidence of poor quality control standards at their MOX plants, point to fundamental problems with the European MOX industry.

Beyond MOX production and quality control problems, in this paper we provide an overview of the general safety issues related to MOX fuel use in nuclear reactors. We then focus on new research on MOX use in Boiling Water Reactors (BWRs) that points to far more serious safety implications than previously considered by the nuclear industry and their national regulators. This issue is also now under consideration by a Japanese court, which is considering the plans of Tokyo Electric to load MOX fuel in only the BWR third reactor in the world that would be loaded with MOX.

As a consequences of the above issues: the low production and quality control standards at European MOX facilities, together with serious safety risks associated with the loading of MOX fuel assemblies BWR's, lead us to conclude that the plans of Swedish utility OKG are irresponsible and should be abandoned. Further, the Swedish regulator SKI, which approved OKG's plans in July 1999 (before the BNFL MOX scandal became public knowledge) was not aware of BNFL's true record of MOX production, nor does it appear to be aware of the problems within MOX production at Belgonucleaire. Any decision by the Environment Ministry to proceed with the use of plutonium MOX fuel use in Oskarshamn reactors would be ill advised and will certainly increase the risk of a catastrophic nuclear accident.

1.0 THE BNFL MOX SCANDAL

The Japanese MOX scandal that engulfed BNFL during 1999-2000 was due to the falsification of Quality Control (QC) data for fuel produced in the Mox Demonstration Facility, MDF. In early September 1999 it was disclosed through media reports that workers at Sellafield had falsified MOX pellet diameter data for fuel due to be shipped to Japan. However the first batch of MOX fuel produced by BNFL for Japan at the same plant had already left the MDF plant and was on board a transport vessel en-route to Japan, when the falsification disclosures first emerged.

The falsification disclosed in September 1999 related to deliberate copying of data sheets for the diameter of the MOX fuel pellets. Workers are required to measure manually a fraction of the total number of pellets and then to record the results. Instead workers were copying identical sheets for pellets measured previously. However, as we detail below, falsification of pellet diameter was only one of a number of violations of QC procedures at BNFL’s Sellafield site.

During the remainder of September 1999, BNFL was under intense public and political pressure in Japan to release all relevant QC data for plutonium MOX fuel that by then had arrived at the Takahama nuclear power plant in western Japan. BNFL complied with demands for the data to be released. Once that data had been released it was clear to the authors of this report, as well as analysts in Japan, that QC data for MOX fuel delivered to Japan had also been falsified. For the following three months, BNFL, Kansai Electric, and the UK and Japanese governments denied that there was a problem with the MOX fuel, and that loading would proceed as scheduled in December 1999.

In November, following further analysis of the BNFL QC data a court action was filed by two Japanese groups, Green Action and Mihama-no-Kai. The groups were seeking an injunction that would prevent the loading of the MOX fuel on the grounds that the MOX fuel contained falsified QC data, and that its use would compromise the safety of the reactor. In mid-December, only days before the Osaka district court was due to rule on the case, BNFL finally admitted that indeed the MOX fuel QC data had been falsified.[1] In the subsequent months more details were to be revealed by the media and Greenpeace that falsification of MOX fuel QC data by BNFL had been underway since at least 1996, including MOX fuel produced for German and Swiss clients.[2] Prompted by the release of QC and production data that until then had been with held on commercial sensitivity grounds, the authors conducted analysis of the production standards and quality control within the European MOX industry - BNFL, French state-company Cogema, and Belgonucleaire.

2.0 EUROPEAN MOX PRODUCTION TECHNIQUES

The technology used by BNFL to produce MOX is called the Short Binderless Route (SBR) process, a dry powder process developed by BNFL from its experience in developing and fabricating MOX fuel for fast breeder reactors. Both the MDF and SMP plants use SBR. The other European MOX producers, Belgonucleaire and Cogema, use a different process, called Micronized MASter Blend (MIMAS).

To manufacture MOX in the SMP, the uranium oxides (UO2) and plutonium oxides (PuO2) are mixed to produce a homogenised powder; these are blended and milled and then tumbled in a spheroidiser to produce granulated powder. During these processes a dry lubricant (zinc stearate) and conditioner (an agent to control porosity) are added. SMP differs from MDF in that no MOX blender is used in MDF. The granulated powder is milled, pressed and sintered in an atmosphere of argon-hydrogen to produce a sintered, fused matrix of ceramic dioxide. The sintered MOX is in the form of cylindrical crystalline pellets. The pellets are produced to dimensions specified by the customer.

In SBR, the milled and blended UO2 and PuO2 powders are fed into a spheroidiser to condition the mixed oxide powder to convert it into a suitable feed for a press. The attritor mill is a high-energy stirred ball mill, using a static mill pot with a stirred ball charge. Its main function is to break down powder agglomerates to produce intimately mixed, finely divided micronised (particles of micron size) MOX powder.[3]

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[1] See, "An Investigation into the Falsification of Pellet Diameter Data in the MOX Demonstration Facility at the BNFL Sellafield Site and the Effect of this on the Status of MOX Fuel in Use", UK Nuclear Installations Inspectorate, February 18th 2000. The MOX fuel under investigation by NII was produced for the Japanese client, Kansai Electric Power Company, KEPCO. The fuel was produced from Japanese plutonium between January and December 1998. It is worth noting that Kansai Electric MOX amounted to around 4 tons of fuel, but that the MDF plant has a capacity of 8 tons MOX each year. BNFL should therefore have completed production of MOX fuel for Kansai Electric after six months, not twelve. Production problems are almost certain to have occurred. The MOX fuel was shipped to Japan between July and October 1999. While the MOX fuel, was in transit to Japan on board the armed nuclear transport vessel Pacific Pintail, it was revealed by the UK newspaper, 'The Independent' on September 14th, that BNFL had falsified MOX Quality Control data for a second batch of MOX fuel then being produced at the MDF for Kansai Electric.

[2] See, for example, Report on the Safety of NNP Unterweser, Incidents at BNFL in connection with the production of MOX fuel assemblies, TUEV, March 28 2000, report to the Lower Saxony Environment Ministry. The TUEV is the Technical Supervision Association contracted by Lower Saxony to assure fuel standards at Sellafield for use in Germany.

[3] See, BNFL, Sellafield MOX Plant (SMP), Special feature, Engineer, No 8, Spring 1996.

The attritor used in SMP is an off-the-shelf model, manufactured by Glebar in the United States and imported by CustomGrind.[4] The attritor mill is widely used in the pharmaceutical industry to produce blends of constituents in a short processing time. A different attritor, manufactured by Giringhelli, is used in MDF.[5] UO2 agglomerates are larger than PuO2 ones and the larger UO2 agglomerates are reduced in size to that of the PuO2 agglomerates. Milling times are less than one hour, very much (up to ten times) shorter than in a conventional tumbling ball mill.

The spheroidiser is static and operates at a much slower speed than the attritor, gently tumbling the powder. The spheroidiser is a vertical disc-shaped chamber fitted with a rotating blade driven from a central axis. The powder tumbles between the blade and the outside wall of the disc. This tumbling process causes the finely divided powder particles to agglomerate, and is supposed to produce a granular material that flows well, a good free-flowing powder feed for the press. Milled MOX powder does not flow very well, which is why it is granulated in the spheroidiser to produce a suitable feed for the press.

The MOX powder is pressed into cylindrical pellets. In the pre-sintered state, the pellets are said to be ‘green’. These ‘green’ pellets are passed on a conveyor belt to a furnace 'boat load station' where they are loaded into furnace 'boats' and taken to the furnace. In the furnace they are sintered in a cycle of about 24 hours in an atmosphere of argon and hydrogen (the gas mixture is 4 per cent hydrogen and 96 per cent argon) to which is added a small quantity of carbon dioxide to control grain growth.[6]

The sinter temperature is up to 1,750 degrees centigrade. After sintering, the MOX pellet is in ceramic form. Conveyors then transfer the pellets to the grinding and inspection stations. They are dry ground using a center-less grinding machine. Boat Unloading and Grinding Lines are designed to deliver the pellets, after they have left the sintering process, in the correct orientation to the grinding machine, which accurately grinds the outside diameter and passes the ground pellets to the inspection stage.

The pellet is supposed to be ground to the dimensions (diameter and length) specified by the customer; the end and radial surfaces are ground to within a final dimensional tolerance as specified. During transport to the grinder the good pellets are separated from the debris.[7] The measurement of the outside diameter allows information to be fed back to the operator controlling the grinding machine. The measurement system includes a mechanism for ejecting pellets that are out of tolerance. During the sintering process the finely divided particles inter-diffuse to form what amounts to a near-solid solution of uranium-plutonium dioxide (UPuO2). Suitable pellets are put into a pellet store until they are required for the production of reactor fuel rods. Unsuitable pellets are supposed to be recycled (see below for details).

The fuel rods consist of a stack of MOX pellets encapsulated in a zirconium alloy (zircalloy) sheath that is purged with helium to form a sealed fuel rod, 4-4.5 meters long. The MOX fuel rods are arranged in square arrays with lightweight bracing to form fuel assemblies. In the fuel rod, the MOX pellets are placed end to end in the sealed zircalloy tubes and the tubes are filled with helium. The pellet stack in a fuel rod is compressed along the axis of the rod by a spring at the end of the rod. The fuel rods are inserted into the reactor core as an assembly; the rods are held in geometric (square) array

[4] See, Brown, C., BNFL, private communication, November 2000.

[5] Ibid.

[6] See, Fujishiro, T., West, J-P., Heins, L., and Jadot, J. J., Overview of Safety Analysis, Licensing and Experimental Background of MOX Fuels in LWRs, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, IAEA-SM-358/III, Vienna, 17-21 May 1999. .

[7] See, Martin, D., MOX – Detail, Design, and Manufacture of Boat Unloading and Grinding Machine, paper presented to the International Seminar on MOX Fuel, Institute of Nuclear Engineers, Windermere, England, 4 June 1996.

by lightweight spacers to form fuel assemblies for a PWR or BWR nuclear-power reactor. A typical MOX fuel assembly consists of a square array of rods: each 4-4.5-metre long rod contains about 300 MOX pellets. For a PWR the array is typically 17 by 17 rods; for a BWR it is 8 by 8 rods. The customers for MOX require that the pellets are soluble in a pure nitric acid solution so that spent MOX fuel rods can be reprocessed.

"BNFL's process, which has been proven successfully during the life of MDF, has been employed in SMP." John Taylor, Chief Executive of BNFL, February 18th 2000.

The Sellafield MOX Plant, SMP, is a scaled-up version of the MDF plant. SMP, designed and constructed by BNFL Engineering Limited, is BNFL's commercial-scale MOX plant. In SMP, which is designed to produce 120 tHM/ year of MOX for PWRs and/or BWRs, the SBR process used in MDF is carried out on a larger scale than in MDF, as appropriate in a commercial-scale plant. MDF uses a 25-kilogram batch size. In SMP, the MOX powder is to be processed through two lines instead of one. Each line in SMP consists of two separate attritor mills and a spheroidiser. UO2, produced by BNFLs Integrated Dry Route, and PuO2, reprocessed from uranium fuels which have typically been irradiated to burn-ups of 45,000 MWd/t, is dispensed into the first mill. The americium-241 content of the PuO2 should be less than 3 per cent so that the average radiation dose to the operators are exposed to radiation doses of less than 5 milli-sieverts per year.[8]

The MOX powder is fed from the mill into a blender. Zinc stearate is added to the blender. The blended mixture is fed into the second mill in the line, into which is also fed Conpor conditioner used to control porosity and pellet density. The first attritor mill will prepare a 50-kilogram batch that will be blended with two other 50-kilogram batches to form a 150-kilogram batch of MOX powder. This is sub-divided into three 50-kilogram sub-batches. The 50-kilogram batches are processed through the second attritor mill and the spheroidiser.

From the spheroidiser, the MOX powder is passed into a feed hopper which feeds it into the pellet press. The press is a hydraulic multi-punch press that can handle soft pellets and transfer the green pellets to the sinter furnace boats. Powder moves from the initial UO2 and PuO2 dispensers through to the press hopper under gravity. In short, three 50-kilogram lots of MOX powder are mixed in the blender to form a 150-kilogram lot. This is then processed in the second attritor mill and spheroidiser to produce granules to feed the press. The second mill and the spheroidiser, which form the conditioning stage, is identical to the single-stage SBR process used in MDF, so that the SMP MOX pellets have the same characteristics as the MDF pellets.

The second process line in SMP is identical with the first - consisting of a mill, a blender, another mill, a spheroidiser, a press hopper and a pellet press. Each line has its own furnaces (each has two high-temperature furnaces) for sintering the pellets and its own grinder. Pellets are measured after they have been pressed and before sintering. A quality control, QC, inspection is conducted on a selection of the pellets after they have been ground. After the QC inspection the pellets are put into the sintered pellet store until they are needed to stack into fuel rods. In each line, the pellets undergo three automatic checks - for pellet diameter, pellet surface and end features (chips, cracks, and so on). Because each line can be used separately, a batch of MOX pellets could be produced for a PWR and another produced for a BWR simultaneously. The two processing lines allow the use of PuO2 batches with different isotopic compositions to produce large MOX batches having almost the same isotopic compositions.

The specified properties of MOX pellets produced by BNFL are: density, 10.45 grams per cubic centimeter (g/cc); the green pellet density is more than 6 g/cc; the average grain size is 7.4 microns,

[8] See, Edwards, J., Brown, C., Marshall, S. J., Connell, M., and Thompson, H., The Development of BNFL's MOX Fuel Supply Business, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, Vienna, 17-21 May 1999.

with a standard deviation of 0.54 micron.[9] A typical MOX pellet for a PWR is 1.0 centimeter long and 1.0 centimeter in diameter and weighs 8.2 grams. A BWR MOX pellet is typically 1.03 centimeters long and 1.04 centimeter in diameter and weighs 9.15 grams.

In summary, SMP consist of two separate lines. Each line contains an attritor mill (fed by UO2 and PuO2 dispensers), a blender, a second attritor mill, a spheroidiser, a pellet hopper, a pellet press, sintering furnaces, and a grinder. After grinding, the pellets go to the sintered pellet store. Zinc stearate and a conditioner are added to the blender and the spheroidiser. Unsuitable pellets, after passing through a pellet crusher, and arisings from the grinder can be recycled through the line. (No fuel supplied to customers from MDF has contained recycled material, although MOX containing up to 30 per cent recycled material has been produced in MDF experimentally.)

The fuel rod, purged with helium, is subjected to a helium leak test, monitored for loose and fixed contamination, tested for rogue pellets, checked for overall length and geometry, X-rayed, inspected for surface finish, loaded into a magazine and stored until required for the production of a fuel assembly. Most of the SMP operations up to the loading of filled fuel rods into fuel magazines and assemblies are carried out in glove boxes.[10]

As described, one line in the SMP could be used to produce PWR MOX fuel assemblies and the other used to produce BWR MOX fuel assemblies. The two rod fabrication and inspection lines are automated, both capable of making PWR and BWR rods. The two assemblies and inspection lines are also automated, both capable of producing PWR and BWR assemblies.

The SMP is a remotely operated (automated) plant relying extensively on a software-based control system for control of the process.[11] The plant is operated from a control room provide with equipment to control the production and inspection stages of the pellets and equipment to monitor and control the environment of the plant.

2.2 Belgonucleaire MOX Production

Two plutonium/uranium Mixed Oxide (MOX) fuel companies operate at the Dessel nuclear site, in the Mol region, near the Belgian border with the Netherlands. Belgonucleaire manufactures plutonium/uranium MOX pellets and fuel rods at the P0 plant. Belgonucleaire is owned by Tractebel - Belgian engineering company, Electrabel - Belgian electrical utility (operator of the country’s 7 nuclear reactors); and CEN/SCK - Belgian nuclear research centre. Both Tractebel and Electrabel are part of the French holding company Suez-Lyonaise des Eaux. After pellet production and fuel rod production is completed, the MOX is transported less than 1000 metres to the Franco-Belge de Fabrication de Combustible (FBFC) International assembly plant, where the fuel rods are put together to form an assembly. This plant is wholly owned by FBFC, a subsidiary of French nuclear companies Cogema and Framatome.

Belgonucleaire's production of plutonium MOX began in the early 1960’s, with new capacity being added in 1973. The facility manufactured MOX fuel for Fast Breeder Reactors (FBRs), including France’s military production reactor Phenix, as well as for Light Water Reactors (LWR), though the actual amount of fuel fabricated for the latter remained relatively small until 1983/84. Ten tonnes of plutonium fuel in total was produced during this ten-year period. In 1984, an initiative was launched between Cogema, the French plutonium reprocessing company, and Belgonucleaire, to form the MOX consortium COMMOX. It functions as the commercial agent for all MOX fuel produced by both Belgonucleaire and Cogema. The MOX plant at Dessel was refitted and renamed P0, with an eventual capacity of 35 tonnes plutonium MOX

[9] See, Edwards, J. and Brennan, J., MOX Fuel Manufacture at Sellafield, paper presented to the International Seminar on MOX Fuel, Institute of Nuclear Engineers, Windermere, England, 4 June 1996.

[10] See, Martin, B. R. and Tilstone, A. J., Licensing of the Sellafield MOX Plant SMP, paper presented to the Nuclear Regulatory Commission, Washington DC, 26 March 1997.

[11] Ibid.

fuel each year. Plutonium MOX fabrication over the next years was largely for French (80%), as well as German and Swiss reactors. From 1996, approximately 70% of Belgonucleaire's fabrication have been for German clients.
The Micronized Master Blend method of MOX production or MIMAS process was developed by Belgonuclaire to replace the former process used at Dessel that directly blended the UO2 and PuO2 powders. MIMAS is also used by Cogema to produce MOX at the Cadarache and Melox plants. The main reason for developing MIMAS was to produce MOX fuel soluble enough for the further reprocessing of spent MOX fuel.

The MIMAS process first creates a primary blend, called a Mastermix.[12] PuO2, UO2 and scrap are balled milled for many hours. The primary blend contains about 30 per cent of Pu. The required final Pu content is achieved by blending, not milling, the primary blend with depleted or natural UO2. MIMAS MOX, therefore, consists of agglomerates of 30 per cent Mastermix in a UO2 matrix. This is different from SBR MOX, which consists of PuO2, UO2 and recycled scrap milled together to produce MOX of the required Pu content.

Whereas SBR uses one blender step, MIMAS uses two blending steps to produce a solid solution of UO2 and PuO2 homogeneously dispersed in a UO2 matrix. The MIMAS MOX is than compacted, sintered and precision ground.

A feature of the MIMAS process is that re-introducing them at the primary or secondary blending steps allows for the recycling of rejected pellets, grinding powder, and other scrap. It should be borne in mind that ease of recycling might influence quality control. If it is harder to recycle, as it is in the SBR process and at the Belgonucleaire MOX plant P0 relative to Melox, there may be a pressure not to reject pellets on inspection in the first place. There may, therefore, be a direct connection between rejection (failure) rates and ease and cost of production, an example of how commercial considerations may affect quality control.

3.0 INHERENT MOX PRODUCTION PROBLEMS

3.1 PRODUCTION PROBLEMS LEADS TO QC VIOLATION

The production of MOX fuel involves the use of an advanced powder technology requiring the mixing, micronizing, pressing, sintering and grinding of two actinide oxides. Experience in other powder processing industries, such as the pharmaceutical industry, suggests that technologies dependent on powder technology are not very reliable.

Small changes in parameters such as humidity, binder concentration and particle size distribution can effect the powder rheology and result in changes in flow rate, poor mixing or powder jams. Such problems are likely to be more severe and more frequent when, as in MOX fuel pellet fabrication, relatively small batches and variable formulations are pelletised. Variations of flow are likely to affect the density and dimensions of pellets and the homogeneity of plutonium distribution in the pellets.

The types of QC inspections of MOX pellet characteristics performed by BNFL are: chemical composition; visual inspection; linear dimensions (pellet diameter and length); geometric density; re-sinter behaviour; end squareness; dish and chamfer dimensions; surface roughness; plutonium homogeneity; and grain size.[13]

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[12] See, Vliet, J., Haas, D., Vanderborck, Y., Lippens, M., and Vandenberg, C., MIMAS MOX fuel fabrication and irradiation performance, paper presented to the International Seminar on MOX Fuel, Institute of Nuclear Engineers, Windermere, England, 4 June 1996.

[13] See, The Nuclear Installations Inspectorate of the Health and Safety Executive, An Investigation into the Falsification of Pellet Diameter Data in the MOX Demonstration Facility at the BNFL Sellafield Site and the Effect of this on the Safety of MOX fuel in Use, February 18th 2000.

The inspection of the fuel rods includes: visual inspection; x-ray inspection; weld metallography; helium leak detection; rod surface contamination; rod length; rod straightness; weld region diameter check; helium pressure test; end plug seal corrosion resistance; and wrong enrichment detection.

Pellet samples are taken for physical and chemical analysis. Pu isotopic composition and U isotopic composition are determined. The total Pu + U + americium content is determined from the sum of individual assay result for these elements.[14] Impurities, gas content, and solubility are also measured.

The oxide-to-metal ratio in a pellet is measured to obtain a measure of stoichiometry, which is important for the physical properties of the fuel and clad corrosion during irradiation. The total amount of Pu and U in the pellets is a crosscheck on stoichiometry and impurity levels. A lapse in quality in any one of these parameters may have extremely serious safety implications and may have consequences which are time consuming and costly to rectify.

Recent revelations of the deliberate and consistent falsification of quality control and assurance data by BNFL for Japanese, German and Swiss clients are of considerable concern.[15] But these represent only part of the problem of assuring the quality of MOX fuel. The quality control procedures themselves as well as their implementation are at fault. The very nature of the fuel pellets and the way they are made preclude adequate quality control procedures capable of being implemented at economic costs.

The advanced powder processing technologies used at MDF are not reliable, particularly so when more than one constituent is mixed together. Faults can occur when a total or partial blockage of the flow of powder occurs or when the components - uranium dioxide and plutonium dioxide in the case of MOX - are incompletely mixed. Experience in other industries, such as the pharmaceutical industry, however, indicates that processes that depend on the flow of powders are far from totally reliable, particularly when these involve the mixing of different constituents.

The need to check the composition of individual MOX fuel pellets is further heightened by the requirement to produce MOX assemblies with a range of plutonium contents. Too many impurities in a pellet could lead to the corrosion of the cladding of the rod and produce unwanted gases. The gas content of the pellets is important; too much gas in the pellet could cause the rupture on heating.

It has been recognised that the production process can produce MOX pellets with variable plutonium content. Variable plutonium content can adversely affect core neutronics, the effects of which have been modelled using a computer simulation.

One of the most important properties of a MOX pellet, from the point of view of reactor operation, is the plutonium content - the weight of plutonium in the pellet as the percentage of the total weight.[16] Inadequate mixing of the oxide powder could result in variations of plutonium content from pellet to pellet. Too much plutonium could produce excessive local heating and affect the core neutronics with adverse safety consequences. More seriously, inadequate mixing of the powder fed into the attritor or inadequate mixing in the attritor may result in inhomogeneous distribution of plutonium within a pellet. Plutonium 'spots' could then arise.

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[14] Opcit, C. Brown, BNFL, November 2000.

[15] The Swiss reactor Benz, operated by NOK, suffered as a direct consequence of BNFL quality control violations. It was confirmed that nitrogen content as well as enrichment of the pellets was out of specification for MOX fuel loaded into the reactor in 1996. NOK also experienced cladding rupture in BNFL MOX assemblies during 1997, leading to the removal of the MOX fuel from the reactor. BNFL confirmed that one of the fuel pins that had ruptured had done so due to 'production problems'. The reactor suffered a similar cladding failure in mid-2000. In total 4 fuel pins were damaged. For one pin, the problem was identified as a welding problem. For two rods 2nd degradation scratches were found out, but to date no further explanation has been provided. The MOX fuel is to be returned to the UK for further analysis.

[16] See, Bairiot, H., Van Vliet, J., Chiarelli, G., Edwards, J., Nagai, S. H., and Reshetnikov, F., Overview of MOX Fuel Fabrication Achievements, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, IAEA-SM-358/III, Vienna, 17-21 May 1999.

A number of variables such as the water content, composition and initial size of the particles used to make the pellets, wear of the attritor mill, and so on, could account for faults in mixing. Variations in them could cause inadequate mixing or even partial or total clogging of the mill. There is little information in the open literature on the efficiency of operation of the attritor mill - how often it jams, how rapidly the mechanism wears, and so on.

The homogeneity of BNFL's MOX pellets is measured using colour alpha autoradiography. Two pellets are sampled at regular intervals for the measurements of PuO2 particle size and Pu concentration. But the frequency at which the checks are done has not been publicly announced. Colour alpha autoradiography is not a commonly used technique and there is some question about its validity for routine measurements. It appears that BNFL examines plutonium 'spots' with diameters up to 400 microns. A thin section (slice) is cut from a sample pellet and then polished. It is then placed in contact in the dark with a photographic film for some days, developed and examined and the size and number of clumps of silver grains in the film assessed. If colour film is used, plutonium shows up as red, so plutonium particles appear as red dots.

Grain size is measured on the same samples as Pu spot size. The samples are etched to reveal the grain structure and the surface is photographed in a microscope, with surface illumination. No information is provided as to how the uniformity of grain size and the size of PuO2 particles are measured across the surface of the polished slice of the pellet. There is also no way of knowing if the particular surface examined is representative of conditions throughout the pellet. This is equally true for the autoradiography check for Pu homogeneity. This, plus the extremely low frequency of all the pellet checks, except for diameter, means that quality control on MOX fuel pellets is inadequate. Assurance that the MOX fuel is therefore safe cannot be given with any confidence.

3.2 Plutonium Inhomogeneity or 'Hot Spots'

The way in which the powder flows during the various stages of MOX pellet fabrication will determine the degree of inhomogeneity in the fuel pellets. The unpredictability of variations in homogeneity has serious implications for quality control procedures. Brief fluctuations in the efficiency of mixing would not be detected unless substantially all of the pellets were inspected; even extended fluctuations would be missed if the samples taken for inspection were not large enough. The uniform distribution of plutonium and uranium oxides in the pellets is extremely important for safety. The cladding of MOX reactor fuel rods could be damaged by local hot spots produced by larger than average plutonium oxide particles on the surface of pellets. Such large particles could accumulate to produce aggregates.

The scientists Gouffon and Merle point out: ***"The size of the aggregate obtained after micronizing (crushing and blending) determines the criterion regarding the energy contained in the oxide pellet during an accident of the control rod ejection type".***[17] According to Schmitz and Papin, "***Accumulations of large plutonium dioxide particles on the surface of the pellet could create hot spots when the fuel is in the reactor and damage the cladding of the fuel rod... Equally important is the evidence that transient, dynamic fission gas effects resulting from the close to adiabatic heating introduces a new explosive loading mechanism which may lead to clad rupture under RIA [accident] conditions, especially in the case of heterogeneous MOX fuel".***[18]

The effects of hot spots on safety become increasingly serious as the burn-up to which the reactor fuel is subjected is increased. Damage to fuel cladding is made worse by the fact that much more fission and

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[17] See, Gouffon, A. and Merle, J.P., Safety problems related to the use of MOX assemblies in PWRs, paper for International Working Group on Water Reactor Fuel Performance, International Atomic Energy Agency, Vienna, 1990.

[18] See, Schmitz, F. and Papin, J., High burn-up effects on fuel behaviour under accident conditions: the tests, CABRI REP-Na., J. Nuc. Materials, Vol. 270, pp. 55-64 1999.

hence more heating occurs at the surface of the pellet than at its center[19]. The risk of serious damage to the cladding is increased for fuels with high plutonium contents and when the fuel is subject to high burn-up.

MIMAS proponents also claim that because of the double blending there is good isotopic homogeneity of the Pu in the product, even with Pu from different origins - light water or gas cooled reactors - or Pu of various forms, including MOX produced in Japan. Also, the micronization step uses only about 15 per cent of the powder.

SBR advocates, however, argue that with ball milling it is difficult to achieve a plutonium agglomerate specification of 400 microns maximum. SBR, they claim, offers a 100 microns maximum and, in practice, there are few agglomerates even as large as 20-30 microns[20]. BNFL claim that it***: "has successfully demonstrated that SBR MOX fuel has no significant plutonium-rich regions of more than 20 microns diameter containing more than 30 percent plutonium".***[21] BNFL state that,

"Analysis of Electron Probe Micro-Analysis (EPMA) maps shows that SBR MOX consists of almost entirely a MOX matrix, with less than 1% of spots containing greater than 20 wt% plutonium, for an enrichment of about 5.5% Pu/U+Pu. The Pu-rich regions in MIMAS MOX form a significant fraction of the fuel, about 25%, with regions up to 100 microns in diameter, while the largest Pu-rich regions observed in SBR MOX are seldom more than 30 microns in diameter".[22]

We argue, however, that the adequacy of the checking procedures does not allow such statements to be substantiated.

In a recent Japanese report from an industry and government funded nuclear research foundation, NUPEC, the size of Pu-rich zones cited above are in fact exceeded.[23] Comparing the sets of data for example it is possible to see that agglomerates of pu-rich zones are up 100% larger with MIMAS MOX than with BNFL, with center pellet data showing dimensions of 140 microns, compared with BNFL spots of 70 microns.

In this latest research it is possible to make a comparison between homogeneity of MOX fuel made with BNFL's SBR, and analyzed by BNFL, and MOX produced at Belgonucleaire by the MIMAS process, and analyzed at the SCK-CEN research center in Dessel, Belgium. Although there appear to be uncertainties with some of the parameters of the analysis, it is noticeable that in terms of pu-rich zones, "hot-spots", the BNFL MOX fuel has smaller dimensional spots. This is not confirmation that BNFL MOX is problem free in terms of homogeneity, far from it. But it is indication that the MIMAS process used by both Belgonucleaire and Cogema is inferior relative to BNFL SBR in this important area.

The problem of homogeneity is further compounded by the low frequency of QC inspection. Homogeneity of Belgonucleaire MOX pellets is measured by using colour alpha autoradiography in which a thin section is cut from a sample pellet, polished and then placed in contact with a photographic film for some days, developed and examined and the size and number of clumps of silver grains in the film assessed. If colour film is used, plutonium shows up as red, so that plutonium particles appear as red dots. This is the same method used by BNFL.

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[19] See, Kameyama, T., Sasahara, A. and Matsumura, T., Analyses of burnup at plutonium spots in uranium-plutonium mixed oxide fuels in light water reactors by neutron transport and burnup calculations, J. Nuc Sci. Technol. Vol. 34, pp. 551-558, 1997.

[20] See, Eastman, R. J. and Tod, S., The Microstructure of Unirradiated SBR MOX Fuel, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, IAEA-SM-358/III, Vienna, 17-21 May 1999.

[21] Ibid.

[22] Opcit, Brown, C., BNFL, November 2000.

[23] See, NUPEC, Report on Fuel Assembly Credibility Substantiation Examination - Mixed Oxide Fuel Irradiation Compilation March 12th 2000.

It appears that only one sample is taken for autoradiography per 13,500 pellets. In a TEPCO report, dated 24th February 2000, it is stated that 32 pellets were checked for homogeneity out of a total of 430,000 (for Fukushima-I-3 reactor fuel). And even for each pellet only a thin slice, representing a very small fraction of the volume of the pellet, is examined. To check only one pellet in 13,500 for homogeneity by autoradiography on only a thin slice of the pellet is inadequate, especially when it is considered that quality control of MOX pellets by necessity needs to be more stringent than of uranium oxide pellets. The Belgian nuclear research center, SCK/CEN, which conducted the analysis cited by NUPEC, conducts alpha-radiography analysis for Belgonucleaire. In a response to an earlier paper of ours, Verwelt, a scientist at SCK state that the,

"MIMAS process is a two-stage blending with thorough micronisation during the first stage. In the final product, occurrence of large, pure PuO2 agglomerates is impossible. During micronisation, all plutonium is mixed with UO2 up to an enrichment of 35%, on sub-micron level. In the finished product, plutonium-rich zones do occur, typically with a diameter between 10 and 50µm, but these are as enriched as the primary mix, with a plutonium-grade of only 35%".[24]

The evidence for this statement however, particularly the claim that the 'occurrence of large, pure PuO2 agglomerates is impossible' is not substantiated. [25]

As already noted, research from SCK itself and cited in a recent Japanese report demonstrate that they find a considerable number of plutonium hot-spots over the 100 micron range, again using only limited alpha-radiography checks. We remain unconvinced that the inspection rate for inhomogeneity conducted at Belgonucleaire/SCK is adequate for a fabrication technology subject to the vagaries of powder flow. Will brief fluctuations in the efficiency of mixing be detected unless substantially all of the pellets are inspected? Do the quality control methods used adequately ensure that pellets do not contain agglomerates with a diameter larger than 550microns, or any other size? On this issue alone we have little confidence in the assurances that MOX fuel is safe to use in reactors.

The information given by Verwelt/SCK in Belgium suggests that about five MOX pellets per assembly will have an isotopic composition which varies by more than three standard deviations from the mean of isotopic composition. On what grounds does Verwelt/SCK view that this number is acceptable from the point of view of reactor safety? In fact, what does Verwelt/SCK believe this variation means for reactor safety?

Verwelt/SCK state that 'commercial confidentiality' prevents them giving details of the quality control procedures used by Belgonucleaire to check MOX fuel pellets. This argument is spurious; given the fact that NUPEC has recently published in considerable detail the methodology of QC alpha-radiography, as well as details on the microstructure of the MOX pellets, including those produced at P0 Belgonucleaire.

3.3 Sellafield Mox Plant, Belgonucleaire and Automation

BNFL

BNFL often claim that because the Sellafield MOX Plant is an automated plant the quality control of the MOX pellets will be much superior to that in the MDF plant. The situation is that in the SMP plant three of the 15 pellet checks in the BNFL quality control list will be automated - the diameter check, a check of the circumference, and inspection of the ends of the pellets. The last two checks look for damage to the surface and ends of the ceramic pellet - chips, and so on. The other 12 checks will be carried out by taking samples in a way similar to that at MDF.

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[24] See, 'Review of the report 'Fundamental Deficiencies in the Quality Control of Mixed-Oxide Nuclear Fuel', Greenpeace International, F. Barnaby/S. Burnie, Marc Verwerft, Peter Vermaercke, Klaas van der Meer, SCK/CEN, Mol, March 20, 2000.

[25] Ibid.

Since the specification of pellet quality will presumably be the same for SMP and MDF pellets, as it is the same SBR technology, the frequency with which the 12 non-automated checks are performed will be similar. The concerns about the inadequacy of important quality control checks (particularly checks for inhomogeneity) of MDF MOX pellets will therefore apply equally to SMP MOX pellets. BNFL's claim that the quality control of SMP MOX pellets will be much superior to the quality control of MDF MOX pellets, just because the plant is automated, cannot be substantiated. We, therefore, strongly disagree with the statement that: "The optimized SBR process (in SMP) reduces the number of quality control samples required and results in a larger quantity of fuel with uniform Pu isotopic composition."[26]

Because the technology used in SMP is the same as that used in MDF, there is no reason to believe that the MOX pellets produced in SMP will be of higher quality than those produced in MDF. In fact, the conditioning stage in SMP is made the same as the single-stage SBR process used in MDF to ensure that the SMP MOX pellets have the same characteristics as the MDF pellets. The production problems discussed above will, therefore, be the same in both the MDF and SMP plants.

Moreover, there is no reason to believe that the quality control and assurance procedures are any better for SMP pellets than for MDF pellets. The main difference is that the surface and end features of the SMP pellets are automatically inspected whereas in MDF the inspections are visual. The diameters of pellets are automatically checked in both the MDF and SMP plants.

Indications that SMP is already in trouble even before it is opened have been revealed in recent weeks. It has been reported that there are problems with the computer hardware and software installed in the SMP during the mid-1990's. A source inside BNFL alleged in a letter to CORE that the SMP is poorly designed and equipped, and that the computer system was already becoming obsolete. BNFL confirmed that it was seeking to replace computer software, "where appropriate".[27]

Belgonucleaire

Belgonucleaire's P0 MOX plant is a 1970's facility that underwent various upgrades during the 1980's-1990's, and consequently cannot be considered a modern MOX plant. In that sense it is of the same generation as the BNFL MDF, that was at the centre of the falsification scandal. However, Belgonucleaire had plans for a new MOX plant, the so-called P1, that would have replaced P0 if it had been built. Original plans were for the P1 to be producing MOX fuel by the mid-1990's. Due to a construction license, and subsequent court action in Belgium, it was never built.[28]

In contrast to the older P0 plant, Belgonucleaire has stated that for the new P1 plant, there would have been 'significant' changes,

"…with respect to P0 (and) the equipment arrangement in the plant and some technological improvements as well as some automization." [29]

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[26] See, Eastman, R. J. and Tod, S., The Microstructure of Unirradiated SBR MOX Fuel, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, IAEA-SM-358/III, Vienna, 17-21 May 1999.

[27] See, Whitehaven News Thursday 11th January 2001. The BNFL source in a letter to CORE (Cumbrians Opposed to a Radioactive Environment), also alleged that parts of the plant had had to be rebuilt, and that roof leaked. It was also stated that during a visit of Japanese officials to the plant they were deliberately steered around the leaking roof !

[28] For more details on this see, "MOX PRODUCTION STANDARDS AND QUALITY CONTROL AT BELGONUCLEAIRE AND THE IMPLICATIONS FOR REACTOR SAFETY IN FUKUSHIMA-1-3", Submission to the Fukushima District Court, Fukushima City, Japan, Dr Frank Barnaby, Oxford Research Group/Shaun Burnie, Greenpeace International December 26th, 2000.

[29] ibid, NRC Workshop p.14.

In addition to admitting that P0 was not fully automated, Belgonucleaire has made it clear that the P1 facility would have had its equipment laid out to the latest standards of industrial engineering design. This would have meant for example that plant ergonomics would have incorporated the latest concepts to maximize production capability. Significantly, one criticism of the discredited BNFL MOX Demonstration Facility (MDF) plant that produced MOX for Kansai Electric is that the ergonomics of the plant led to problems for the operators and workers.

Having failed in its attempt to construct P1, Belgonucleaire was left with only the existing P0 plant to fulfill its orders. Thus Belgonucleaire was forced to resort to maximizing its existing production capacity in an attempt to secure new, but obviously smaller contracts for fuel supply. We have made the case before that meeting production targets became a critical factor for MOX manufacture.[30] We argue that in the case of BNFL, the basic inability to manufacture MOX fuel and the small size of the production capacity relative to the contract size (16 tons capacity over two years, for a Japanese contract of 8 tons for Kansai Electric) were a central factor in BNFL's falsification of QC data and the passing of fuel that should have been rejected. Rather than the maximum of 6 months that the production of the Takahama-4 MOX fuel should have taken instead it took BNFL 12 months to fabricate the fuel, due to production problems within the plant.

In the case of Belgonucleaire the situation has been somewhat different as its production record over the last ten years demonstrates (over 378 tHM MOX produced between 1990-1999). Unlike BNFL, which had few contracts for MOX manufacture and was not even able to produce what it had contracts without delays, Belgonucleaire was under different pressures in particular due to its production capacity being fully booked until 2005. This has meant that P0 has been operating at close to licensed capacity for successive years, including during the manufacture of TEPCO MOX in 1997-1999. The nominal capacity of the plant after refurbishment and capacity increase is 35tHM/y, with a license maximum of 40tHM/y. The production of Fukushima-I-3 MOX fuel, coincided with the highest production output in Belgonucleaire's history for three successive years, yielding a total of 110.2tHM. That is, in the three years between 1997-1999, during which the production of Japanese MOX fuel, including for Fukushima-I-3 and Kashiwazaki-kariwa, took place, P0 produced 5tHM in excess of its nominal capacity.

Belogonucleaire would no doubt argue that this is evidence of the reliability of the fuel manufacturing process at P0. However, it also can be argued that this gives the manufacturer little flexibility if it is to meet its customer's delivery requirements and thus failure of fuel and delays in production must be minimized. In addition, Belgonucleaire has admitted that maintenance and repair of equipment cause delays in production. It is for this reason that it has established an interconnection between the two lines for pellet and rod production, which ***"allows the bypass of some of the part of the equipment…with a reduced impact on the output of the plant."***[31]

3.4 PROBLEMS OF DRY GRINDER TECHNOLOGY

"…BNFL stated that due to the performance of the grinder at MDF, there was no regularity to the diameter distribution and that random sampling inspection by variables could not be applied." Kansai Electric Report March 1st 2000.

During the BNFL/Kansai Electric MOX falsification scandal, it became public that BNFL's method for grinding and the sintered MOX pellets caused the pellets to chip and crack. This, it is suggested by Kansai Electric, was the reason why the laser measurement for all pellets was altered to measure the diameter in a two-millimeter central band rather than at both ends and middle. Kansai Electric further explained that pellet diameter adjustment is difficult using a dry grinder, and it is for this reason that a total pellet measurement is carried out. However it has also been pointed out by the authors in submissions to the court

[30] see, 'Fundamental Deficiencies in the Quality Control of Mixed Oxide Nuclear Fuel', Dr Frank Barnaby/Shaun Burnie Greenpeace International, Fukushima City, Japan, March 27th 2000.
[31] See, 'Experience and Trends at the Belgonucleaire Plant', Dermaix,Eekhout,Pay and Pelckmans, BN, Dessel, Belgium, June 1999.

in Japan, that BNFL pellets have been reported as being flowerpot or hour glass shape, requiring the company to alter the points on the pellet which are measured during the total pellet measurement.

The reason for the damage to the surface of MOX pellets appears to be due to the fact that commercial MOX facilities use the dry grinding process. This was not always the case, and may be an example where scaling up production of MOX for commercial use has had a negative impact on the quality of the final product. It is known for example, that MOX production in the past in Japan for the experimental Advanced Thermal Reactor (ATR) Fugen used a wet grinding process.[32] The uranium fuel industry uses a wet grinding process.

In the fabrication of MOX pellets, the risk of employing wet grinding is that there is an increased risk of criticality as the wet process binds together an amount of plutonium MOX powder. However, the wet grinder has clear advantages over dry grinding in terms of pellet quality. This is due to the fact that the pellet does not come into direct contact with the grinder, but rather is ground to the required dimension by coming into contact with the wet layer that builds up between it and grinder, the so-called 'Michelin Effect'. The interaction between the pellet and grinder during dry grinding is more damaging to the pellet surface than wet grinding. However, the safety risks in terms of criticality posed by the use of a wet grinding process when handling large quantities of plutonium MOX fuel were a significant factor in the commercial MOX producer's fuel opting for the dry grinder. As with BNFL, Belgonucleaire and Cogema utilise dry grinders in their MOX facilities.

As we have learnt from other sources, BNFL MOX pellet production technology, including the grinder, is incapable of making pellets that are consistently of a cylindrical diameter. In 1995 Mitsubishi Heavy Industries conducted an inspection at the MDF. During that investigation they noticed that BNFL had not automated the random QC sampling measurement. BNFL cited that there was plutonium contamination that prevented the automation (this would have meant installing cabling through the glove boxes) and the automation was not done. Following on from this, Mitsubishi identified a significant problem in BNFL's inability to produce pellets within a narrow range of diameter. Specifically, Kansai reports states,

"It was also confirmed that the ability to manufacture pellets with a small variation in diameter was not sufficient." [33]

Mitsubishi reported this to Kansai Electric at the time, but they took no further action.

Confirmation of the pellet diameter problem is given by the German Inspection Association, TUEV in its recently completed report into BNFL MOX production, prompted by the falsification scandal involving Kansai Electric. TUEV were requested to investigate after the disclosure that MOX fuel supplied to Germany contained falsified QC data (the reactor concerned Unterweser was closed down in February 2000 to remove the BNFL MOX fuel affected). Its report is currently being examined by the Lower Saxony government, as well as the committee established by the Federal Environment Ministry into MOX quality control and reactor safety. Every year since 1994 the TUEV, together with Siemens, has detected defects in the quality assurance management system used by BNFL. TUEV criticised BNFL that quality control and production were not sufficiently independent of each other. Only after fuel production had begun for the German reactor, Unterweser, in 1996, was TUEV informed that changes had been made; though falsification was to later occur.

Significantly, TUEV had earlier been informed that the application of ***a "strict diameter tolerance of +/- 10 micrometers caused a high rejection rate."***[34] In other words, a strict standard was too difficult for BNFL to meet. TUEV agreed to a lowering of standard by a full 30% to +/- 13 micrometers. When TUEV received

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32 See, "Operational experiences in MOX fuel fabrication for the Fugen Advanced Thermal Reactor, p.109, T. Okita, S. Aona, K. Asakura, Y. Aoki, T. Ohtani, Japan Nuclear Fuel Cycle Development Institute, Ibaraki-ken, Japan. IAEA-SM-358/3 June 1999 IAEA Conference.

33 opcit, Kansai Electric report, March 1st, "Qualification Inspection for MDF, 3.4.2.".

34 opcit. TUEV, p.38.

the final data on the fuel, which we estimate was in late 1997 when the fuel was delivered to Germany, they criticised nine deficiencies, including three diameter documentation data, (though they have yet to explain what precisely they found). TUEV appears to have failed to take this investigation further, nor did it notice that pellet density data had been copied on two lots of MOX fuel.[35] Thus as early as 1997 problems in the QC data, were detected, not by the UK regulators, Nuclear Installations Inspectorate, (NII)[36] but by a German inspection agency. Having said this, both Siemens the fuel contractor with BNFL on behalf of German utility PreussenElektra, for MOX produced for Unterweser NPP, and the TUEV, do not escape criticism. A large question remains to be answered as to the commitment of Siemens to high fuel standards and why it permitted these problems to persist over the last five years. Unbelievably, the TUEV did not visit Sellafield until February 2000 to take up investigations, this despite knowing as far back as 1997 that there were problems with the QC data.

Almost certainly, OKG and SKI have not considered these issues in their plans to use BNFL MOX fuel. It is worth noting that despite months of investigation by the UK Nuclear Installations Inspectorate at the BNFL MDF, their inspectors were not aware of the changes made by BNFL until it was disclosed in the media. In addition, the problems that were identified by Siemens and TUEV during 1997 appear not to have been communicated to the Swedish Ministry. We are unaware of the extent to which OKG knew of these problems when preparing its submissions to the Swedish Environment Ministry.

"BNFL's process, which has been proven successfully during the life of MDF, has been employed in SMP." John Taylor, Chief Executive of BNFL, February 18th 2000.

Throughout the last five years, BNFL has promoted its MOX technology as superior to its rival producers, Cogema and Belgonucleaire. Specifically the Short Binderless Route (SBR) developed and used in the MDF, has been incorporated in the yet to be opened Sellafield MOX Plant (SMP).[37]

Problems with the technology in the MOX Demonstration plant have been acknowledged by BNFL. At the same time, in recent weeks it has been revealed that the pellets produced by the SBR method led to pellets that are not shaped correctly. Our analysis of the TUEV report suggests that the pellets in fact may not be 'flowerpot shaped' as earlier reported[38] but were more 'hourglass", with both ends having different dimensions from the central point in the pellet. It is the central 2mm belt that BNFL take their all-pellet measurement. This may be one reason why pellets measured in the all-pellet stage, subsequently failed the random sampling QC stage. Automated measurement, as noted by Siemens and TUEV, is therefore no guarantee of either the reliability of production or the accuracy of measurement. It is not a QC check.

However, the NII, either ignorant or choosing to ignore the failure of all-pellet automated measurement noted above, states,

"…one point worth noting is that in the new Sellafield MOX Plant, currently being commissioned, the inspection processes for MOX pellets, rods and assemblies are designed to be almost fully automated: this should prevent the falsification of data of the kind described in this report."

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[35] It is worth noting that BNFL in its report on the MOX falsification issue, claim that "the data obtained on the key quality characteristics during the fabrication of several tons of MOX fuel pellets" in its MDF plant shows that, "No difficulties have been experienced controlling the pellet dimensions, the density…" And yet they have falsified density data. NII's acceptance without apparent questioning BNFL assurances on the quality of the MOX product is exposed once again as flawed.

[36] See, "CRITIQUE OF NII REPORT ON BRITISH NUCLEAR FUELS MOX FUEL QUALITY CONTROL", Aileen Mioko Smith – Green Action/Shaun Burnie-Greenpeace International, April 11th 2000

[37] for more details on the technology including comparative analysis with the Cogema/BN MIMAS process see, Fundamental Deficiencies in MOX Quality Control…(opcit.)

[38] see, The Independent newspaper on March 7th 2000.

Clearly the NII cannot be relied upon to give accurate assessments on the quality of MOX fuel production at BNFL's Sellafield site. They have no mandate to do so, given the reality that the no reactor in the UK uses or plans to use MOX fuel.

4.0 REGULATORY OVERSIGHT IN MOX FUEL STANDARDS

This section discusses the fact that there are no international agreed standards for MOX fuel, and that the producers and clients agree to standards that suit commercial rather than nuclear safety interests. It is pointed out that there are no sanctions imposed on MOX producers for violating QC procedures, highlighted by the continued ISO accreditation of the discredited BNFL MOX plant.

The BNFL/Kansai Electric case exposed to public scrutiny for the first time many important issues to do with the standards of manufacture of MOX fuel. One of the most important was the lack of domestic and international regulatory control over MOX fuel standards.

The ISO states that one of the principles followed in developing international standards is "consensus". It says, ***"The views of all interests are taken into account: manufacturers, vendors and users, consumer groups, testing laboratories, governments, engineering professions and research organisations.***[39] In everyday life certification of a product to a given quality assurance standard, is an indication that it can be expected to perform reliably. The World Standards Services Network states,

"For the user [certification] provides assurance that the product purchased meets defined characteristics or that an organisation's processes meet specified requirements. Certain product certification marks may represent an assurance of safety and quality".[40] There is no doubt that badly made nuclear fuel can affect the safety of a nuclear reactor. The UK's Nuclear Installations Inspectorate (NII) states,

"The quality of nuclear fuel loaded into a reactor can potentially affect safety as well as the performance of the reactor. We are concerned only with safety and expect the purchaser to require and confirm appropriate quality assurance arrangements to ensure that only fuel of the correct standard is applied." [41]

The UK Environment Agency states,

"In manufacturing MOX fuel, BNFL is required to meet the customer's specification for fuel composition and design. The fuel specification is fundamental to the safety case for the operation of a nuclear reactor. It is for the customer to satisfy the regulatory authorities in its own country that the fuel is safe to use in the customer's reactors. The Agency takes the view that the regulatory authorities in countries to which BNFL might return plutonium in the form of MOX fuel would not permit such fuel to be loaded in reactors unless they were satisfied that the safety risks associated with its use were low." [42]

It seems reasonable to expect that nuclear regulators worldwide should ensure that operators of their licensed nuclear sites only buy fuel that has been certified to strict quality assurance standards. One might expect that even greater care would be taken in the manufacture of plutonium fuel (MOX) than with ordinary uranium fuel, because of the increased complexity and greater safety risks. However, this is not the case.

The regulators in Belgium, France, and Japan have not set any product standards for MOX fuel. In Japan, for example, the law is vague about requirements for MOX fuel. It states that plutonium uniformity, ***"must not be a hindrance for practical use"*** and that deviations in measurements and consistency ***"must not be***

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[39] see, www.iso.net

[40] see, www.wssn.net

[41] see, Letter from UK Nuclear Safety Directorate to Greenpeace UK, 15th March 2000.

[42] see, UK Environment Agency (1998) document containing the Agency's Proposed Decision on the Justification for the Plutonium Commissioning and Full Operation of the Mixed Oxide Fuel Plant, BNFL, PLC, Sellafield, October 1998, para. A4.149.

remarkably large". [43] However, these vague requirements do expose the complacency of the safety authorities in overseeing the quality of plutonium MOX pellets. There is no way to judge how badly made the pellets would have to be before Japanese regulators would consider them unsafe for use in a reactor.

There is also no international product standard for MOX fuel pellets. In fact the technical working group of the International Organisation for Standards responsible for "Measurement methods for chemical and physical characterisation of MOX pellets" was only set up in March 1998. So far it has published no standards at all.[44] This working group is run by BNFL, ***"…on behalf of…" the British Standards Institute (BSI)***[45]

There is one ISO standard on the plutonium dioxide powder to be used for making MOX fuel pellets, but it is limited only to "Guidelines to help in the definition of a product specification". The Standard states ***"As it cannot be considered a standard product, the plutonium consequently cannot form the subject of general supply specifications, as is the case for uranium".*** [46]

This means that the regulators have in effect left it up to Belgonucleaire, BNFL, Cogema and its customers to agree the specifications for MOX fuel amongst themselves. [47] This decision is a major regulatory failure. This failure has led to no one taking responsibility for the threat to nuclear safety that could be posed by badly manufactured fuel. This is not perhaps surprising given the monopolistic nature of the nuclear fuel industry.

MOX manufacture is not widespread, and therefore OKG's options for MOX manufacture are limited to two suppliers - BNFL and Belgonucleaire/Cogema.[48] It is not in the interests of OKG to question too severely the safety or reliability of its only MOX fuel suppliers, when they have no alternative suppliers.

It was only after the final admission by BNFL in December last year that it had falsified QC data that the scale of the MOX production problem emerged. It was also only after this that Kansai Electric announced that it would not be using the BNFL MOX fuel.

On March 1st 2000, Kansai Electric released a report on the MOX falsification scandal in Japan. The report states that Mitsubishi Heavy Industries (MHI) carried out an inspection of BNFL's MDF in 1995. Kansai Electric's report states, ***"[MHI confirmed that [BNFL's] ability to fabricate pellets with a low spread of diameters was insufficient, and we received a report about this, but we did not take sufficient steps to have BNFL improve their production ability".***[49] In other words, BNFL's customer knew that there was a fundamental production problem with the plant, yet did not require this problem to be solved. The regulators in Japan, who are ultimately responsible for checking the safety of Kansai Electric's reactors, either did not know or did not care.

Once a product standard has been set - even if it is only agreed between the fuel manufacturer and its customers - someone has to check that the standard is being met. According to the British Standards Institute (BSI) a quality management system is ***"…a common-sense, well documented business system;***

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[43] Ministerial ordinance about technical standards concerning power generating nuclear fuel. Article 5 (4),(5) (Ministry of International Trade and Industry Ordinance, June 15th 1965)

[44] see, ISO to Greenpeace, 23rd February 2000.

[45] see, BSI to Greenpeace, 8th February 2000.

[46] see, ISO 13463: 1999, "Nuclear-grade plutonium powder for fabrication of light water reactor MOX fuel - Guidelines to help in the definition of a product specification."

[47] see, for example NII (2000a), "An investigation into the falsification of pellet diameter data in the MOX Demonstration Facility at the BNFL Sellafield Site and the Effect of this on the safety of MOX fuel in use", 18th February 2000.

[48] Belgonucleaire and Cogema jointly provide MOX fuel services through the COMMOX consortium.

[49] see, KEPCO 2000, An Investigation into the Problem of MOX Fuel Fabricated at BNFL (Interim Report), 1 March 2000, Section 3.4.2, translated and summarized by Green Action.

applicable to all business sectors, which helps to ensure consistency and improvement of working practices, including the products or services produced." [50]

Lloyd's Register Quality Assurance (LRQA) has independently certified the MOX Demonstration Facility (MDF) at BNFL's Sellafield site to the international management standard ISO 9002. LRQA states that companies which undergo certification achieve benefits to their business which include, "improved efficiency and less production waste; improvement in system control; increased customer satisfaction; increased market share; reduction in customer audits."[51]

The ISO states that, ***"the objective is to give the organisation's management and its customers confidence that the organisation is in control of the way it does things.[52]*** There is no doubt that by falsifying quality assurance data on MOX fuel sent to Japan and Germany, BNFL has lost the confidence of its customers. In a memo to BNFL's Chairman, Hugh Column, BNFL's communications advisors state,

"BNFL is in a crisis - a crisis of confidence affecting every aspect of the company…This crisis of confidence is shared by most, if not all, the company's stakeholders. Key customers, the DTI and many politicians, have lost confidence with senior management. Internally, employees at Sellafield have lost confidence in corporate management." [53]

Yet, unbelievably, BNFL still retains accreditation to the quality management standard ISO9002 on the MDF, as well as for other plants at Sellafield.

BNFL's MOX Demonstration Facility was awarded ISO9002 in 1998[54] although the first falsification of quality assurance data in the MDF noted by the NII was in 1996.[55] Falsification of quality assurance on Japanese MOX fuel occurred whilst the MDF was accredited to this international quality management standard, yet appears not to have been detected by LRQA during its 6 monthly visits. Even after the public discovery in 1999 of the falsification of QC pellet diameter data, and when BNFL's claims that fuel sent to Japan had not been affected were proved false, LRQA did not remove the certificate.

The award or retention of ISO9002 by a company, whether it be BNFL, Belgonucleaire or Cogema clearly should not provide any confidence at all to either its customers, regulators or the public that procedures are being followed, or that public statements are correct. This should come as no surprise as ISO standards are not legally enforceable, and in addition have no sanctions attached if violated.

The nuclear industry worldwide and its regulators have never bothered to agree international quality assurance standards for plutonium fuel. Belgonucleaire, Cogema and BNFL customers have accepted weak standards as well as failing to notice when things go wrong. Regulators have turned a blind eye, even when presented with the evidence, or argued that the issue is not their responsibility. Quality Assurance bodies have been secretive and viewed their role as acting solely in the interests of the MOX producers and customers. Significantly recent reports suggest that the non-nuclear industrial community in Japan at least are increasingly questioning ISO standards, in particular the 9000 series, Toyota has reported earlier this year that they will not be using ISO 9000. The following description of ISO 9000 could have been drafted specifically to describe QC in the MOX industry,

"It makes people do things that makes them worse and stops them doing things that would make them better."[56]

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[50] see, www.bsi.org.uk, "ISO 9000 - Questions and Answers."

[51] see, www.lrqa.com "Services"

[52] see, www.iso.ch, "Publicizing your certification".

[53] see, Bell Pottinger (2000), Communications Recommendations, Reputation Recovery (draft 2), 22 February 2000.

[54] see, BNFL(1998), Annual Report and Accounts.

[55] see, NII(2000a), para 103.

[56] see, "The quality you can't feel", The Observer, J. Sneddon, 19th November 2000, citing the book, 'The case against ISO 9000', Oak Tree Press.

Although the UK's Nuclear Installations Inspectorate (NII) went out of its way to assure Kansai Electric and MITI, that the fuel was safe to use, they had no practical experience to issue such an assurance. In fact the NII is explicitly exempted from assuring the safety of nuclear fuel intended for overseas customers. The UK itself does not use any plutonium MOX fuel in its reactors, nor are there any plans to do so. (Even though the stockpile of plutonium in UK is projected to increase to as over 100 tonnes within the next few years.) Thus any assurance on fuel standards given to the Swedish government by the UK regulators should be seen in this context.

It is worth highlighting that SKI explains that OKG, if it proceeds with MOX fuel production at Sellafield or Belgonucleaire, ***"expects to be following the manufacturing process through regular factory visits and follow up of documentation***." SKI should understand that Japanese representatives were permanently based at Sellafield and Dessel during production of MOX fuel for Kansai Electric and Tokyo Electric, and did not detect falsification during that time. Further, SKI by this statement are already indicating that the production standards and quality control is not an issue for them in reality and will be left to the customer and producer. In fact SKI states that has confidence in the MOX manufacturing processes at the facilities proposed partially since "both manufacturers have licenses to produce MOX from the authorities of their respective countries." This confidence is clearly misplaced, given the "buyer beware" attitude that the regulators clearly embrace, as shown above.

5.0. OVERVIEW OF SAFETY ISSUES RELATED TO MOX FUEL USE

The production standards required for the manufacture of plutonium fuel (MOX) fuel are considerably higher than for those of the conventional uranium industry. Not only is this due to the different characteristics of the manufacturing process, including the need for two different oxide powders to be mixed together thoroughly, but also because the fuel itself performs differently across a range of parameters.

Reactor operators and MOX producers generally claim that burning MOX in light-water reactors designed to use ordinary uranium oxide fuel does not pose any additional safety problems. These claims are usually based on the fact that plutonium is produced continually during the operation of a reactor fuelled conventionally with uranium oxide and that some of this plutonium undergoes fission's, typically accounting for approximately one third of the total fission's. It is concluded that plutonium fission's in LWRs do not constitute a new problem. Such arguments are flawed.

In a typical uranium oxide fuel element, subjected to a burn up of 35,000 megawatt days/ton, the amount of plutonium accumulated in the fuel element while in the reactor will be about one per cent of the weight. In a typical new MOX fuel element, plutonium will account for five per cent or more.

Two types of causes contribute to an increase in risk in reactors burning MOX compared to those reactors burning uranium oxide fuel. Firstly, the fact that MOX fuel pellets are constructed from two actinide oxides rather than one makes fabrication and quality control considerably more difficult for MOX compared with uranium oxide fuel. Secondly, differences in properties of plutonium and uranium in the core of a MOX-burning reactor alter the functioning of the reactor with adverse consequences for safety.

Compared with uranium oxide, plutonium oxide has a melting point, which is more than 30 degrees Centigrade lower; it is less effective at conducting heat; and it releases a greater volume of gaseous fission products. These differences reduce the safety of reactors using MOX fuel. The properties, for example energy and number, of the neutrons produced during the fission process of MOX fuel, or neutronics, will reduce the effectiveness of control of the reactor. Also, neutron irradiation will do more damage to the materials used to construct the core and its surroundings. This over a period of time could have adverse consequences for reactor safety.

Reactivity coefficients of MOX fuel are more negative possibly causing variations in power output, which could result in a reduced margin for the shutdown of the reactor in an accident. These issues are likely to increase the speed with which an accident evolves and increase the severity of an accident. This factor is more important for BWR's, such as Oskarshamn, than PWRs, because they experience higher energy releases during accidents, particularly reactivity insertion accidents.

Core physics determine that MOX fuel behaves significantly different from uranium oxide fuel in the following main ways:

The probabilities (cross-sections) of nuclear fission's following the absorption of a neutron and the cross sections of the capture of a neutron without fission for plutonium isotope 239, 240 and 241 are very different from those of uranium-235, the uranium isotope involved in fission in the reactor. The plutonium-239 cross section, for example, is greater than that of uranium-235 in the thermal field.[57] Because of these differences in cross-sections, MOX fuel absorbs more neutrons of low energy so that the average energy of the neutrons in the core of the reactor is greater. There is a shift of the neutron spectrum towards the epithermal neutron field with energies in the range of 0.1-100 electron volts.[58] The boron in the reactor control rods is less able to absorb the more energetic neutrons thus the control of the reactor is less effective. For the same reason, boron introduced into the coolant of pressurized water- and boiling-water reactors in an emergency shutdown will be less effective. This reduction in the efficiency of control rods and borated coolant can have an adverse effect on reactor safety.

The curves of the cross-sections of plutonium-240 show resonances for epithermal neutrons. This means that the negative reactivity required to go from full to zero power will be increased.[59] This reactivity is compensated by control rods so that the total neutron absorbing capacity of the control rods in the fuel assemblies must be greater than those used for a core fuelled only with uranium dioxide

Plutonium MOX fuel compared with uranium dioxide fuel produces fewer delayed neutrons.[60] The fraction of delayed neutrons for plutonium-239 (0.0021) is more than three times less than that for uranium-235 (0.0065). Thus the neutron flux in a core fuelled with MOX will tend to increase more quickly than one fuelled with uranium dioxide. This makes the control of a reactor fuelled with MOX more difficult than one fuelled with uranium dioxide.

Because of differences in neutronic behaviour between uranium oxide and MOX fuel assemblies, there will be increases in neutron fluxes at interfaces in the reactor. Normally, an attempt is made to reduce this effect by using different plutonium contents in each MOX assembly. Nevertheless, some increase in peak thermal fluxes will occur at the hottest spots in the fuel rods, impairing operating flexibility.[61]

The release of fission gases in MOX fuel is greater than in UO2 fuel for a given burn-up. Helium is produced in greater quantity in MOX fuel than in UO2 fuel. The main contributor to helium production in MOX is cerium-242. The amount of helium produced depends on burn-up as well as the amount of plutonium initially in the MOX. Xenon and Krypton are produced in quantities greater that the amount of

[57] see, Graves, H. W. Jr., Nuclear Fuel Management: Chichester, John Wiley and Sons, 1979.

[58] see, ibid. Grave et al.

[59] see, Report of the International MOX Assessment, Comprehensive Social Impact Assessment of MOX Use in Light Water Reactors: J. Takagi, M. Schneider, F. Barnaby, I. Hokimoto, K. Hoskowa, C. Kamisawa, B. Nishio, A. Rossnagel, M. Sailer, Citizens' Nuclear Information Center, Tokyo, November 1997.

[60] see, Vliet, J., Haas, D., Vanderborck, Y., Lippens, M., and Vandenberg, C., MIMAS MOX fuel fabrication and irradiation performance, paper presented to the International Seminar on MOX Fuel, Institute of Nuclear Engineers, Windermere, England, 4 June 1996.

[61] Opcit, Grave et al.

helium produced. The helium/xenon+krypton ratio is typically 0.07 at a burn-up of 40,000MWd/t, rising to 0.18 at 60,000MWD/t.[62]

To summarise, plutonium MOX reactor fuel has physical properties that are different from ordinary UO2 reactor fuel, affecting the thermal and mechanical performance of the fuel rods. The main effects are:

- reduction of the control rod and neutron absorber worth's because of the higher thermal absorption cross-sections of Pu relative to those of U, reducing the margin for shutting down the reactor;[63]
- MOX has greater fission cross-sections at higher neutron energies than UO2 fuel, resulting in the coolant void coefficient of reactivity being less negative for MOX than for UO2 fuel;
- the harder neutron energy spectrum in MOX fuel, and the consequent higher neutron energies, may increase the damage done to the pressure vessel of the reactor by neutron irradiation,[64] because the thermal conductivity of MOX, compared with UO2, is reduced, the energy stored in the fuel rods in a loss-of-coolant-accident is increased;
- higher temperatures also increase the release of fission gases from MOX fuel and increase the pressure in the rods; plutonium hot spots may affect the behaviour of MOX fuel[65] and the cladding of MOX rods during reactivity accidents, a problem that has not been resolved[66]);
- the different concentrations of fission products and actinides in MOX fuel may increase the severity of a reactor accident; the larger amounts of actinides in MOX fuel the decay heat of the fuel rods will be greater;
- the much larger amounts (by between 5 and 22 times) of actinides in MOX fuel may increase, by about one-third, the number of fatal cancers produced by a reactor accident. [67] Releases of up to 5 per cent of the actinide inventory of a PWR core may be released in severe accidents, compared to up to 10 per cent of the actinide inventory of a BWR core, such as that Oskarshamn.

In the context of accidents in reactors fuelled with MOX, it should be noted that, although MOX ceramic melts at a temperature of about 1,800 degrees Centigrade, surface oxidation occurs at the much lower temperature of about 250 degrees Centigrade if the fuel is exposed to air. At relatively low temperatures, exposed MOX pellets produced respirable-sized particles following relatively short exposure periods. For example, 1.87 per cent of the initial mass was rendered respirable when MOX fuel was exposed at 430 degrees Centigrade for 15 minutes, compared to 0.01 per cent at 800 degrees Centigrade.[68] A particle with a diameter less than 3 microns can be inhaled into the human lung, with a resultant substantially increased public health risk of lung cancer due to the alpha radiation.

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[62] see, Lippens, M., Maldague, Th., Basselier, J., Boulanger, D., and Mertens, L., Highlights of R&D Work Related to the Achievement of High Burnup with MOX Fuel in Commercial Reactors, IAEA/OECD-NEA International Symposium on MOX fuel cycle technologies for medium and long term deployment: experience, advances, trends, International Atomic Energy Agency, IAEA-SM-358/III, Vienna, 17-21 May 1999.

[63] Opcit, IMA, Takagi et al

[64] see, United States Nuclear Regulatory Commission, Mixed-Oxide Fuel Use in Commercial Light Water Reactors, Memorandum from Executive Director for Operations, United States Nuclear Regulatory Commission, Washington DC, April 14, 1999.

[65] Willermoz, G., Bethoux, P., Bruna, G. B., Castelli, R. and Serant, D., Modelling of manufacturing fuel heterogeneities in a PWR via a stochastic - perturbative method, Prog. Nuc. Energy, Vol.33, pp. 265-278, 1998.

[66] see, Grandjean C. and Lebuffe C., High Burnup Fuel Cladding Embrittlement under Loss-of-Coolant-Accident Conditions, Proceedings of the Topical Meeting on Safety of Operating Reactors, ANS Seattle, September 17-20, 1995.

[67] see, Lyman, E. S., The Impact of the Use of Mixed-Oxide Fuel on the Potential for Severe Nuclear Plant Accidents in Japan, Nuclear Control Institute, Washington DC, October 1999.

[68] see, Seehars, H., and Hochrainer, D., Durchfuhrung Experimenten zur Unterstutzung de Annahmen zur Freisetzung von Plutonium bei einem Flugzeugabsturz, Franhofer-Institute, SR 0205A, March 1982.

The submission of OKG to the government and the report of SKI recommending the use of MOX fuel that concludes, ***"…that use of MOX fuel can take place safely"***[69] is flawed in its failure to acknowledge important general safety issues in relation to the use of MOX fuel.

6.0 REACTOR SAFETY ISSUES SPECIFIC TO BOILING WATER REACTORS

The manufacture of nuclear fuel must, as far as possible, provide high assurance that in the event of a severe nuclear accident the nuclear fuel remains intact and in a geometry that is conducive to heat removal until safety systems become available. If significant numbers of fuel failures occur early in the accident, fission products will be released and changes in fuel geometry may interfere with the flow of coolant through the core, "increasing the risk that fuel heat-up will continue until the irreversible core melting and quantitative fission product release occur."[70]

In new research submitted to a Japanese court in January 2001, by Dr Edwin S. Lyman, Scientific Director of the Nuclear Control Institute, the case is made that the implications for reactor safety are directly related to the problems of QC. The issue under investigation relates to BWR's such as Oskarshamn where a transient that can initiate a nuclear accident known as a power oscillation "anticipated transient without scram" (ATWS). Given the serious implications of Lyman's research, we highlight some of the issues he so far has addressed.

It is known that if there is a failure to successfully scram a reactor, the average core power and fuel temperature will rise until fuel cladding failures occur and fuel fragments are expelled, resulting in fuel-coolant interactions, steam explosions, pressure pulses and blockages of coolant flow. Hence the need to ensure the ability of the fuel to withstand the stresses induced by this type of accident.

Why this issue is so pertinent to Oskarshamn is that a relatively low-temperature mechanism has the potential to cause BWR fuel cladding to fail during a power oscillation, known as pellet-clad mechanical interaction (PCMI). As Lyman notes,

"In unirradiated fuel, a gap on the order of 150 microns is present between the fuel pellet surface and the interior surface of the fuel cladding. During irradiation, the fuel pellet initially shrinks, but eventually begins to undergo thermal expansion, as well as swelling from the accumulation of fission product gases…As a result, the pellet-clad (P/C) gap first increases then decreases. If the gap eventually closes, the pellet and cladding come into hard contact. Further pellet expansion exerts tensile stress on the cladding (and the cladding exerts compressive stress on the pellet). PCMI can cause cracking of both the fuel and the cladding, ultimately inducing cladding failures if it is sufficiently severe."[71]

Though PCMI is rarely a problem, a power oscillation could cause this rapid fuel temperature and pressure increases, which could accelerate pellet expansion and gap closure, inducing a PCMI. Brittle fracture of the cladding could also occur if there is insufficient time for the cladding to heat-up.

Until recently the nuclear industry and research community had considered that PCMI was not a significant problem for BWR's because cladding creep down is lower and P/C gap correspondingly wider. This will as a result of recent Japanese government funded research have to be revised. Lyman, reports that experiments conducted by JAERI (Japan Atomic Energy Research Institute) Nuclear Safety Research Reactor (NSRR) have,

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[69] See, "APPLICATION FOR LICENSE TO USE MOX FUEL IN OSKARSHAMN 2 OR 3, Review pro-memoria from SKI, addressed to The Government via Environment Ministry, 30th June 1999.

[70] see, 'The Importance of MOX Fuel Quality Control in Boiling-Water Reactors", research paper draft, in progress, Dr Edwin S. Lyman, Scientific Director, Nuclear Control Institute, Washington DC, December 14th.)

[71] ibid.

"…demonstrated this is not the case for high-burnup uranium fuel."[72]

The experiments led to the severe failure of the fuel when exposed to conditions simulating a BWR power transient in the NSRR.[73]

During the experiment, 100% of the fuel was finely fragmented and dispersed into the reactor coolant. As reported by JAERI, the fuel was reduced to a powder. As Lyman notes, ***"if this had occurred in a power reactor, it would have caused severe pressure pulses, distorting the core geometry and affecting the ability to operate the reactor control system."[74]***

MOX fuel use in Oskarshamn will increase the risk of a severe core melt accident caused by power oscillation. Lyman summarizes the principal reasons:

- the use of MOX will increase the severity of a power oscillation transient - due to a more negative void coefficient and the smaller size of delayed neutron fraction caused by MOX loading, this will increase the frequency and amplitude of the power oscillations; in addition the thermal conductivity of MOX fuel is lower than uranium fuel, leading to increased fuel temperature and power increases reducing the time that operators will have to intervene;

- the performance of MOX fuel is inferior to uranium fuel of the same burnup, in such areas as fuel swelling and fission gas release (CABRI test results in France clearly demonstrate this). There is no equivalent data for BWR MOX. Lyman notes that JAERI tests with BWR MOX fuel at the NSRR in Japan have been on fuel with a burn-up of 20MWd/t, half that which TEPCO has been licensed to operate its BWR at Fukushima-I-3. It is noted that in two of the JAERI tests the pellet clad gap closed and PCMI occurred, causing significant residual strain on the cladding. The P/C gap for the ATR MOX fuel had shrunk by around 50%, or 75 microns during the base irradiation.[75]

Significantly, as Lyman points out, BWR uranium fuel at far higher burn-up (45GWd/t) and with similar initial P/C gaps and cladding material to the ATR MOX fuel did not exhibit P/C gap closure or significant cladding strain. This demonstrates further that the effects seen in very high burnup uranium fuel, above 50GWd/t, occur at much lower burn-ups for MOX fuel.

In conclusion, Lyman notes that,

"… the vulnerability of BWR fuel to PCMI during oscillation-type transients appears to be quite sensitive to the initial P/C (pellet-clad) gap of the fuel, very tight control of the P/C gap during fuel fabrication, as well as thorough understanding of its evolution during fuel irradiation, are essential for providing high assurances in safety of high burnup BWR fuel during transients…An uncertainty of 20 microns in the pellet diameter, which is the current tolerance for the MOX fuel destined for Fukushima, appears to be highly significant with regard to P/C gap evolution, and therefore unacceptably large."[76]

In assessing the risks of MOX fuel a number of years ago, a nuclear engineer, now a member of the German government nuclear safety division observed that,

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[72] see, T Fukeda et al, JAERI, "High Burnup BWR Fuel Response to Reactivity Transients and A Comparison with PWR Fuel Response," Transactions of the 28th Water Reactor Safety Information Meeting, Bethseda, MD: U.S. Nuclear Regulatory Commission, October 23-25, 2000.

[73] Ibid.

[74] see, W. Yuen and T. Theofanous, "A Scoping CFD Evaluation of RIA Consequences," U.S. Nuclear Regulatory Commission, undated, (on the NRC website) as cited in Lyman, December 14th.

[75] see, opcit, T. Fukeda et al, "JAERI Research on Fuel Behaviour During Accident Conditions," as cited by Lyman.

[76] Opcit, Lyman.

"In critical situations, the requirements of which transcend normal levels - in particular reactivity incidents and transients - even small reductions of safety margins in control can lead to serious problems and accidents. The danger that incidents for which the plant is designed develop into major accidents is thus increased by the use of MOX."[77]

The decision to proceed with the loading of MOX fuel in OKG's BWR Oskarhshamn unit 2 or 3 reactor in Sweden is one we believe will inevitably increase the risks and consequences of a serious nuclear accident. The MOX production and QC control problems that have emerged over the past 18 months only increase the accident risk for any reactor using such fuel.

7.0 LIMITED BWR MOX FUEL EXPERIENCE AND MANUFACTURE

"The MOX FA (fuel assembly) for the insertion in a BWR is in general much more complicated because of the much higher heterogeneity in comparison to PWR." Siemens, June 1999.[78]

Only two Boiling Water Reactors in the world are currently operating with MOX. BNFL has no experience manufacturing MOX fuel for commercial BWR nuclear power plants, and Belgonucleaire has very limited experience in BWR MOX manufacture.

The production standards required for the manufacture of MOX fuel are considerably higher than for those of the conventional uranium industry. Not only is this due to the different characteristics of the manufacturing process, including the need for two different oxide powders to be mixed together thoroughly, but also because the fuel itself performs across a range of parameters differently from uranium fuel. As noted by Siemens, MOX fuel intended for use in BWR's require a more complicated process of assembly than that for PWR. This is due to the higher heterogeneity in BWR's, including the need for a larger range of plutonium enrichments relative to PWR MOX fuel. Siemens fuel specialists note that 6 different MOX rod types and 1 additional Gd (gadolinium) poisoned fuel rod (to avoid power peaks around the water channel and to reduce initial criticality) make up the typical BWR 9X9 assembly.

Given this additional complexity, it is worth noting that Belgonucleaire, though it promotes itself as the major MOX manufacturer historically, has considerable less experience in BWR MOX production compared with PWR fuel.

Of the 418tHM MOX produced by Belgonucleaire since 1986, only 10% have been BWR fuel. In terms of total MIMAS BWR MOX production, the comparisons are even less favourable. Through the end of 1999, a total of 839 tonnes of MOX had been produced by Cogema's Melox and Belgonucleaire (combined figures for Cadarache are not included, however no BWR MOX fuel is produced at this site), of which 5% was BWR. COMMOX (excluding Cadarache) manufactures MOX fuel for clients in Germany, Switzerland, Belgium and France (and Japan).

Out of all the MOX produced by COMMOX only 4% have been loaded into BWR reactors. Prior to the manufacture of the Tokyo Electric Fukushima-I-3 MOX fuel, Belgonucleaire had only produced commercial BWR MOX fuel for one client in Germany. Belgonucleaire does not have extensive BWR MOX manufacturing experience. Nor can it be said that electric utilities have extensive experience of BWR MOX use. The Fukushima-I-3 reactor will be only the third commercial BWR in the world to load MOX fuel. In total 34.6 tons of MIMAS BWR MOX have been produced by Belgonucleaire for the German power plant, Gundremmingen (two reactors). This corresponds to 228 assemblies, containing 16,843 fuel

[77] See, Dr Michael Sailer, member of the German government's Commission for Nuclear Safety, including member of the working group on plutonium and spent fuel management, see, The MOX Industry, IPPNW, 1994.

[78] see, "Advanced Mixed Oxide Fuel Assemblies with Higher Plutonium Content for Light Water Reactors", W. Stach, Siemens AG, Untemehmensbereich KWU, Erlangen, Germany, June 1999.

rods. In addition, a further 7.5 tonnes of MOX were produced for Fukushima-I-3 and Kashiwazaki-Kariwa-3, corresponding to 60 fuel assemblies containing 2752 rods.[79]

In SKI's submission to the Swedish Environment Ministry, they conclude that,

"SKI judges that both manufacturers of MOX fuel (BNFL and Belgonucleaire) have a large experience manufacturing such fuel and that production can occur in a safe fashion, and have high quality.(6) Both manufacturers have license to produce MOX fuel from the respective authorities of the their country. SKI judges that both fuel manufacturers of MOX fuel have a large experience of fuel manufacture."[80]

Given the evidence of major violations of QC procedures by BNFL over years, evidence of manipulation of QC by Belgonucleaire, as well as significant problems with production standards, the above statement wholly misrepresents the reality of MOX production. The fact that BWR MOX fuel manufacturing and experience of use is so limited, raises further questions over the robustness of SKI MOX assessment submitted in July 1999.

8.0 CONCLUSION

The safety of conventional thermal nuclear reactors fuelled by MOX is seriously compromised by two important considerations: difficulties in the fabrication and quality control of MOX fuel pellets and differences in the behaviour of plutonium and uranium in the reactor. These problems are compounded when it comes to the manufacture of BWR MOX fuel.

No significant safety analysis has been done by either MOX producers or regulators into the implications of quality control and quality assurance for the risk of accidents when MOX fuel is used in reactors. To compound this failure, the Swedish regulators SKI which assessed the OKG MOX plans in 1998 and early 1999 did so prior to the disclosures of BNFL falsification, and the subsequent investigations by the Japanese government, British government regulators and independent analysis. INSERT DIMA SECTION SKI…

Clearly while conducting its assessment of OKG's license application, SKI were relying upon information provided to it by OKG, and perhaps BNFL and Belgonucleaire. At least in the case of BNFL it has now been proven that they were at the same time falsifying QC data for MOX fuel for their most important Japanese clients, Kansai Electric. Less than two months after the issuing of its approval for OKG's plans BNFL was revealed to have deceived its major client. This led to investigations by the UK's NII, as well as Japan's Ministry of International Trade and Industry, German state government of Lower Saxony, and Switzerland's HSK, as well as research by specialists in Japan, and the authors of this report. An illustration of how serious the events of September 1999 were to become is illustrated in a memo to BNFL's Chairman, Hugh Collum, BNFL's communications advisors state,

"BNFL is in a crisis - a crisis of confidence affecting every aspect of the company…This crisis of confidence is shared by most, if not all, the company's stakeholders. Key customers, the DTI and many politicians, have lost confidence with senior management. Internally, employees at Sellafield have lost confidence in corporate management." [81]

All of this appears to have by-passed SKI and OKG. Greenpeace enquiries last week to SKI on whether subsequent to the July 1999 submission to the Swedish government, they had provided further information on MOX manufacturing at Sellafield in light of the scandals involving falsification, were met with the

[79] See, Belgonucleaire own data released to Japanese legislators, BN-02-0005-E.

[80] Opcit, SKI submission to Environment Ministry 30th June 1999.

[81] See, Bell Pottinger (2000), Communications Recommendations, Reputation Recovery (draft 2), 22 February 2000.

answer, ***"…no we have not because the government has not requested it."***[82] SKI have failed to grasp the scale of events that have unfolded since their MOX approval recommendation to the Swedish Environment Ministry. In the opinion of the authors both OKG and SKI have great deal of explaining to do. Clearly plans for MOX fuel use in Sweden should be abandoned.

[82] Personal communication between Dima Litvinov, Greenpeace Nordic with Jan In de Bertou, author of SKI submission to Thursday 9th 2001.