FUNDAMENTAL DEFICIENCIES IN THE QUALITY CONTROL OF MIXED-OXIDE NUCLEAR FUEL

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INTRODUCTION

In September 1999 it was revealed that British Nuclear Fuels (BNFL) had falsified quality control data during the production of plutonium Mixed Oxide fuel (MOX) for a Japanese client. In subsequent months further details have emerged on the quality assurance standards applied by BNFL, as well as their Belgium competitors, Belgonucleaire. Just prior to the release of this report, it has been revealed that MOX fuel produced by French company Cogema contained false quality control data to be used in a German nuclear power plant. The scandals have shaken public confidence in Japanese industry plans to use MOX fuel, as well as industry confidence in the reliability of BNFL as a fuel supplier. The majority of reports, including from the UK governments Nuclear Installations Inspectorate (NII), have tended to define the problem as being due to worker boredom, poor ergonomic design of the MOX plant, and inadequate management supervision during MOX production. However this Greenpeace assessment, based upon the publicly available literature points to a far more serious problem: that current MOX quality control standards are low. In addition, it is suggested that the actual production technology currently utilized cannot guarantee a reliable product in important areas vital for the safe operation of a reactor using MOX fuel.
Without rigorous quality control standards, the reliability and safety of MOX fuel cannot be guaranteed, with major implications for nuclear reactor safety and public health.

The quality assurance data that has so far been disclosed has given independent analysts a unique opportunity to assess both the standards applied by BNFL and Belgonuclaire, as well as an insight into the quality of the actual production. However, BNFL, Belgonucleaire (and the French plutonium company, Cogema) never intended to make public the data that has now been released, and they continue to withhold extensive and important data on the production standards applied and quality assurance. Citing commercial confidentiality, they are rightly under intense pressure to release all relevant data. This report is the first attempt to assess what information they have released to-date. It has enabled us to reach some preliminary conclusions, but raises many more important questions that remain to be answered.

MEANING OF QUALITY CONTROL

Quality control involves a system of inspection, analysis and action applied to a manufacturing procedure in which a small fraction of the product produced is inspected to make an estimate of the overall quality of the product. The changes, if any, which must be made in the manufacturing operation to achieve or maintain the required level of quality are then determined. Normally, each of the items produced has a set of specifications, which must be satisfied to meet the needs of the customer. The specifications may be set by the customer, with reference to the intended use of the product, by the relevant manufacturing organization, according to its understanding of the customer's intended use, or they may be legally defined. Quality control is then the set of activities in manufacturing the item, which has the aim of ensuring that the specifications of the finished product are satisfied.

The term quality assurance includes all the technical and management aspects of product quality and safety during the entire manufacturing process - design, specification, research and development, manufacturing and use stages. In other words, quality control refers to the technical aspects of the inspection procedures, including analysis and action, while quality assurance involves actions by, and is the responsibility of, the relevant managers of the manufacturing firm, including the active supervision of the staff doing the quality control operations.

From time to time, quality standards must be reviewed and quality operations undertaken to ensure products remain satisfactory to the customer. Because manufacturers generally want to make a profit, they aim to perform quality control with minimum costs, to obtain the specified product quality at the lowest feasible cost.

Inspection and testing of the product are, for cost reasons, normally performed at various points in the production process, so that it can be seen if the specifications are being conformed with at all stages of production. This avoids waste; it can be costly if non-conformity is determined at the final stage of production. Usually, therefore, there are key points in the production process at which inspection and checking are essential. If they are to be effective, quality control operations should be incorporated into the overall organization. Moreover, the manager in charge of quality control should report to the most senior manager responsible for manufacturing the product (typically, the works manager), who should be responsible for both the quantity and quality of production.

The range of characteristics of the product checked, the frequency of checks, and their thoroughness, should be determined by the consequences of the use of a faulty product. If, for example, the safety of people would be jeopardized by a faulty product, the quality control and quality assurance must be particularly stringent. Where relevant, the type, range and frequency of checks should be based on estimates of the degree of risk to people that is acceptable. Faulty mixed-oxide (MOX) nuclear fuel pellets - containing large agglomerates of plutonium, for example - could produce hot spots, which could damage the cladding of fuel rods and threaten the safety of the reactor using the MOX fuel. The quality control of MOX pellets should, therefore, be determined by estimates of the risk to reactor safety of defective MOX pellets.

This should be done separately for each type of check made on the pellets. In other words, the fundamental principle of quality control (particularly the detail of characteristics checked and the frequency of the checks) and quality assurance of a product like MOX fuel should always be based on risk assessment and not on cost. The evidence, described below, suggests that this is not happening in the production of MOX fuel. Quality control and assurance procedures are not based on acceptable risk analysis; they are determined instead by cost considerations. If they were based on safety rather than cost, MOX production may well prove to be not viable economically.

THE MOX PRODUCERS

European commercial MOX fabrication plants are operated by: British Nuclear Fuel Limited (BNFL) at Sellafield, England; Belgonucleaire at Dessel, Belgium; and Cogema at Marcoule and Cadarache, France.

The Belgian MOX production plant at Dessel, PO, is operated by Belgonucleaire, started commercial operation in January 1985. It can produce 35 tons of heavy metal (LWR) MOX pellets and rods per year (tHM/y). Final assembly of the fuel is conducted at the nearby Franco-Belge de Fabrication de Combustible International (FBFC) site. The French plant at Marcoule, MELLOX, started commercial operation in 1995. It has a current operating capacity of 100 (tHM/y), though Cogema plan that it eventually produces 250 tHM/y. Cogema’s other MOX plant is located at Cadarache, and started operating in 1969. It has a nominal capacity of 40 tHM/y but produces significantly less than this. It can produce MOX for fast breeder reactors, using the COCA process, and MOX for LWRs, using the MIMAS process (see below).

The MOX Demonstration Facility (MDF) at Sellafield operated by BNFL, originally a fast breeder reactor (FBR) fuel manufacturing plant during the 1970’s and 1980's. After 1989, its capacity was increased and converted to LWR MOX production, which began in October 1993. It has a capacity of 8 tHM/y and is a pilot (demonstration) plant devoted to LWR MOX fuel. The Sellafield MOX Plant (SMP) was completed in 1997, but has not yet been fully licensed to operate. Owned by BNFL, it has a capacity of 120 tHM/y.

MOX PRODUCTION TECHNOLOGIES

Two different processes are used to produce MOX fuel in European plants. BNFL uses the Short Binderless Route (SBR) process; Belgonucleaire and Cogema use the Micronized MASter Blend (MIMAS) process. SBR was developed by BNFL as a result of its experience in developing and fabricating MOX fuel for fast breeder reactors. BNFL claims that, by the nature of the process, the MOX fuel pellets produced by the SBR are more homogenous than those produced by MIMAS.

SBR uses an attritor mill to blend the uranium dioxide (UO2) and plutonium dioxide (PuO2) powders and a spheroidiser to condition the blended mixed oxide (MOX) 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, that breaks down powder agglomerates and is supposed to produce intimately mixed, finely divided micronised (particles of micron size) MOX powder. The size of PuO2 particles is reduced to that of UO2 particles. Milling times are less than one hour, very much (up to ten times) shorter than in a conventional tumbling ball mill. The milled powder from the attritor is passed to the spheroidiser that is also static and operates at a much slower speed, 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.

After the MOX powder is pressed into a cylindrical shape it is sintered to produce the ceramic MOX pellet that is then precision ground to specified dimensions. During the sintering process the finely divided particles inter-diffuse to form what amounts to a near-solid solution of uranium-plutonium dioxide.

After pressing, the pellets, green in colour, are passed on a conveyor belt to a furnace 'boat load station' where they are loaded into furnace 'boats' and taken to the furnace where they are sintered in a cycle of about 24 hours in an atmosphere of argon and hydrogen. Conveyors then transfer the pellets to the grinding and inspection stations. They are dry ground using a center-less grinding machine. Suitable pellets are put into a pellet store until they are required for the production of reactor fuel rods. Unsuitable pellets are recycled.

In BNFL's MOX Demonstration Facility (MDF), a 25-kilogram mixture of MOX powder is produced in an attritor mill. It is then blended with two other 25-kilogram batches in a blender to produce a 75-kilogram batch of MOX powder of uniform composition. This MOX powder is then divided into three 25-kilogram batches. Each of these is processed through an attritor mill and spheroidiser to produce the feed for the press. In the planned Sellafield MOX Plant (SMP), the SBR process has been scaled up using larger batches. In SMP, the MOX powder is to be processed through one of two separate attritor mills and spheroidoisers. 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 will be processed in three 50-kilogram batches through the second attritor and spheroidiser [1]. Because each attritor and spheroidoiser can be used separately, a batch of MOX pellets could be produced for a PWR and another produced for a BWR simultaneously.

The 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 MELLOX plants. The main reason for developing MIMAS was to produce MOX fuel soluble enough for the further reprocessing of spent MOX fuel.

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 primary, or master, blend is obtained by ball milling. This so-called micronization stage produces MOX powder of high plutonium content (30 to 40 per cent Pu). The required plutonium content (5 per cent, for example) is obtained in the second blending step. The MOX is than compacted, sintered and precision ground.[2] A feature of the MIMAS process is that re-introducing THEM at the primary or secondary blending steps easily recycles 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, 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.

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. 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". Comments on measurements of plutonium homogeneity in MOX fuel pellets are made in the section below on autoradiography.

MOX fuel rods are produced by placing MOX pellets end to end in sealed tubes, typically made from zircalloy, filled with argon. The fuel rods are held in geometric array by spacers to form a fuel assembly for a nuclear-power reactor. A typical MOX fuel assembly consists of a square array of rods (17 x 17): each 3-metre long rod contains about 300 MOX pellets.

QUALITY CONTROL AND ASSURANCE OF MOX FUEL

It has already been mentioned that, for the safe operation of a reactor using MOX nuclear fuel, the quality control and quality assurance of the fuel pellets and rods are a matter of considerable importance. The MOX fuel pellets must be produced to very demanding tolerances. This is more important for MOX fuel than for ordinary UO2 fuel; the fact that MOX fuel pellets are constructed from two actinide oxides rather than one makes fabrication considerably more difficult for MOX compared with uranium oxide fuel.

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

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[1] BNFL, 'Special feature - Sellafield MOX Plant (SMP)', Engineer, No. 8, Spring 1996.

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

of pellets and the homogeneity of Pu distribution in the pellets. For this reason, quality control of MOX pellets should be more stringent than for uranium oxide pellets.

Linear dimensions, density, bulk composition and homogeneity of MOX pellets should all be assured to within very narrow limits. 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 at BNFL's MOX Demonstration Facility (MDF) are therefore of considerable concern. 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. If the attritor mill at the MOX plant is operating correctly it should produce fine, uniformly mixed "micronized" (micron-sized) particles which can be made to flow like a liquid through subsequent processing stages until they are pressed and heated to form the final sintered (heat fused) cylindrical pellet. 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.

A crucial question is: Given the potential problems inherent in the production process of MOX fuel pellets, are the quality control and quality assurance procedures sufficiently effective to give confidence that MOX fuel is no threat to reactor safety? The information available so far suggests that current MOX production techniques and quality control are indeed a threat to the ‘safe’ operation of a reactor.

BNFL claims 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, surface finish or thermal stability of the fuels made in MDF. The standard deviation on pellet diameter is 0.004 millimeters and on geometric density is 0.032 grams per cubic centimeter. The surface roughness of pellets produced in the plant averages 0.43 micro-radians with a standard deviation of 0.159 micro-radians."
- "The hydrogen content of the pellets produced was low (with a mean value of 0.27 parts per million and a standard deviation of the mean of 0.14) and tests showed that pellets produced do not pick up hydrogen or moisture when stored in air. The oxygen/metal ratio was consistently close to 2.000".
- "No manufacturing difficulties have been experienced controlling the fissile material content of the fuel within the specified enrichment tolerances"
- "The grain size averages 7.4 microns with a standard deviation of 0.54 microns. For pores with a diameters greater than 5 microns the median pore size has never exceeded 15.4 microns during the production to date (1996)" [3].

The raw data on which these conclusions are drawn are not publicly available and therefore no independent analysis can be done. But there is some data from other sources showing that the BNFL statement about its ability to control pellet dimensions is inaccurate. On 1 March 2000, the Japanese utility Kansai Electric (KEPCO) released a report on the falsification by BNFL of MOX fuel pellets inspections. The report questions the competence of NII in investigating the falsification scandal. According to KEPCO, in 1995 Mitsubishi Heavy Industries (MHI), acting on behalf of KEPCO, questioned the ability of BNFL to make pellets with accurate diameters. It was also found that the MDF was incapable of conducting the preferred method of quality assurance due to insufficient performance of the pellet grinder. Moreover, random sampling for the Japanese fuel was not conducted properly at BNFL. BNFL intentionally passed pellets that should have failed the quality control inspection. Pellet diameter measurements were not conducted according to the agreed procedure. When inspectors found that a diameter measurement of a pellet was not within specification, rather than rejecting the pellet which was the agreed procedure, they turned the pellet 90 degrees in order to find a measurement that would be within the specification and therefore allow the pellet to pass inspection. This raises the suspicion that there was pressure from management to pass these inspections to avoid having to re-fabricate pellets and lose time and money.

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

Further questions about the reliability of the MOX pellet production process was raised recently when it was reported that many pellets were emerging from the grinding process out of shape. The problem dates back to the early operation of the plant and confirms the doubts expressed by MHI around the same time. Large numbers of pellets that should have been cylindrical had instead one end significantly wider. When the automatic laser micrometer measured “top”, “bottom” and “middle”, it rejected many pellets as being outside the tolerance range in safety specifications. Unable to correct the problem, BNFL instead altered the measuring technique, by moving the “top” and “bottom” readings from the pellets to within two millimeters of the center reading, so that pellets that would have failed were passed.[4] BNFL claims that the explanation that it is normal for the pellets to be "plant-pot" shaped, but that following grinding the pellets are “not flowerpot shaped” is not credible. Automatic laser inspection takes place after grinding. Questions over the effectiveness of both the sintering technology and the grinding tools arise out of this information. BNFL claimed that the micrometer was rejecting the pellets because it was measuring the chamfer edge, again this does not appear credible. The measurement points are set to give assurance on the pellet size. The chamfer, or rim, is important to check separately, but it is not a factor that should effect the diameter measurements of the pellet, and it certainly is not a justification for measuring only the central diameter of the pellet.

PARAMETERS CHECKED DURING MOX PRODUCTION

A number of characteristics of the MOX pellets produced by BNFL are, of course, checked before they are put into store until required for loading into fuel rods. The rods also go through a quality control procedure. Some information about the quality control procedures is in the open literature,[5] but not nearly enough to comprehensively review the effectiveness of quality control. The rationale given for this lack of information is 'customer confidentiality'. The BNFL MOX pellet specification, according to which the pellets are produced, is 'developed in conjunction with' BNFL's customers and 'the details of this specification are confidential'.

Some information about quality control is given in the report of the British Nuclear Installations Inspectorate (NII) of its investigation of the falsification by BNFL of MOX pellet data.[6] However, although more information is available than previously it is still insufficient for a full independent assessment to be made of the effectiveness of the quality control of MOX pellet production.[7] There are questions about the independence of the NII, including concerns that the "nuclear safety watchdog may have become too close to BNFL to regulate it effectively"[8]. The NII failed to identify the problem about the falsification of data on MOX pellet inspections at BNFL for three years, and has still not adequately addressed fundamental issues, such as the underlying motives for the falsification.

According to the NII report, the types of inspections of pellet characteristics performed by BNFL are: chemical composition; visual inspection; pellet length; geometric density; re-sinter behavior; end squareness; dish and chamfer dimensions; surface roughness; plutonium homogeneity; and grain size.
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.

Fuel Rod Parameter - The weight of each fuel rod is an important measurement to ensure that the correct number of correctly sized pellets, have been introduced into the fuel rod. It would also monitor for the illicit replacement of fuel pellets with blanks of a similar size. The latter is of considerable importance, for safeguards reasons, to ensure that all the plutonium entering the MOX fabrication process can be accounted for in the completed fuel assemblies. Unless this is accurately done it will not be known whether plutonium has been lost or stolen in the MOX fabrication plant, a serious consideration for this fissile and highly toxic element. The NII report does not say whether or not all MOX rods are weighed.

The entire length of each rod is X-rayed. This will, however, not detect a uranium oxide pellet that has been inserted into the rod to replace a MOX pellet. MOX fuel assemblies are inspected for: dimensional envelope; channel spacings; cleanliness; control rod withdrawal force; and surface finish.

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[4] “BNFL lowered safety standard to boost output”, The Independent, March 7th 2000

[5] opcit, BNFL, 'Special feature - Sellafield MOX Plant (SMP)', Engineer, No. 8, Spring 1996.

[6] 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', 18 February 2000.

[7] opcit, BNFL, Special feature.

[8] Morgan, O., 'Safety Chiefs too close to BNFL', The Observer, Business Section, 5 March 2000.

Pellet Content Analysis - The NII report states that pellet samples are taken for physical and chemical analysis. The check of chemical composition includes the ratio of Pu isotopes to U isotopes, Pu enrichment, metal content ratio, oxygen to metal ratio, impurities, gas content, and solubility. The measurements are carried out in a laboratory that is NAMAS accredited. But no indication is given of how frequently the measurements are done. Without this information it is not possible to comment on how effective the checks are.

The measurements of the metal (plutonium and uranium) content of the pellets and the pellet's oxide-to-metal ratio are important because they give further information about the plutonium content of the pellets.
The bulk composition (the masses of plutonium and uranium dioxides in the pellet) is also an important parameter. Too little plutonium in the pellets and the purchasers are not getting value for money; too much and serious local overheating could result. Indeed, it has been recognized that the production process does produce MOX pellets with variable plutonium content.

Variable plutonium content can adversely affect core neutronics, the effects of which have been modeled using a computer simulation.[9] 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. The plutonium content of each fuel pellet must also be determined as part of the accountancy procedure, used for safeguards purposes, for this material. 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.

Pellet Size - MOX pellets are visually inspected for defects on the surface. The lengths of pellets in a random sample are measured using a micrometer with an accuracy of 1 micron. The length must be within a specified range, not given in the report, with a 95 per cent confidence level. The sample consists of 20 pellets taken from a 'lot' of 4,000 pellets, or 0.5 per cent of the total.

The diameter of the MOX pellets is checked using an automated inspection system. The system uses a laser micrometer to make three separate measurements of the diameter of a pellet. A pellet for which one or more of the measurements is out of specification (given by the customer) is supposed to be automatically rejected by a gate mechanism. The specification range for diameters of Kansai pellets is plus or minus 0.0125 millimetre. BNFL claims that the accuracy of the laser micrometres is plus or minus 0.002 millimetres. However, recent reports have revealed that BNFL altered the measuring points to one central diameter check, following the rejection of an undisclosed quantity of MOX pellets when measuring the top, bottom and middle of pellet.[10]

The diameters of 200 pellets out of a 'lot' of about 4,000 pellets (about 5 percent) are also measured manually - top, middle and bottom diameters are measures on each of the 200 pellets. Two operators are involved in this check; it takes them about two hours to measure the 200 pellets. This statistic indicates the man-hours, and therefore high cost, of checking large numbers of MOX pellets. The numbers involved are very high indeed. The eight MOX assemblies sent from Sellafield to Japan in 1999, for example, contained a total of about 614,000 MOX pellets (17 x 17 rods; 300 pellets per rod, and 8 assemblies = 614,000 pellets).

The size of pellets is important because a pellet, which is too small, may rattle about within the fuel rod and cause serious wear in the fuel cladding. On the other hand the swelling of a pellet to a size which is too large as a consequence of neutron irradiation or heat may also cause damage to the fuel cladding. Apart from visual inspection, looking for chips, cracks, defects in the surface, and distortions of shape, the diameter measurement is the only check done on all the pellets. All other checks are done on samples, often representing only a very small percentage of pellets.

The initial visual check inspects only one side of the pellet (the pellets are on trays). A second visual check is done on a sample of pellets. The NII report fails to address the question of whether these visual checks are adequate.

Weight And Density - The weight of the pellets in a random sample - 20 pellets out of 4,000 (0.5 per cent) is measured using an electronic balance. From this and the measurements, using a micrometer, of outer diameter and length, the density of the pellet is calculated. The measurement of weight will be very accurate but the other measurements will be less so. The density, according to the NII report, must be within the specification range with a 95 per cent confidence level. This is not a very strict level - 99 per cent would be more reassuring. A high or low density could indicate faults in pellet fabrication. High-density pellets may swell excessively; pellets with low density might split. The fact that it has now emerged that BNFL falsified density data for MOX pellets supplied to German client, PreussenElektra raises further questions about the reliability of BNFL production and quality control standards.

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[9] Willermoz, G., Bethoux, P., Bruna, G. B., Castelli, R. and Serant, D., 'Modeling of manufacturing fuel heterogeneity's in a PWR via a stochastic - perturbative method', Prog. Nuc. Energy, Vol. 33, pp. 265-278, 1998.
[10] opcit, The Independent, March 7th 2000.

Thermal Stability - The thermal stability of the pellets is measured following the exposure of the pellets to a high temperature. The report says, "ten pellets samples are taken at regular intervals agreed by the customer. All pellets must meet specification limit on geometric density following high temperature, extended sintering." The question of how frequent a "regular" interval is not answered. No figures are given as to the percentage of pellets checked and the NII report does not explain if the dimensions of the pellets are measured with the density. Thermal stability is a very important property of reactor fuel and more details about the measurement should be given.

The dish dimension (the punch used to produce the pellet produces a dish-like indentation at each end of the pellet) and the chamfer dimension are checked but only on samples. Random samples of six pellets per lot of 4,000 are taken. The chamfer height and length are measured using image processing with a precision of 0.01 millimeters. Dish depth is measured using a depth gauge with a precision of 1 micron.
After press tools are changed a random sample of 20 pellets is taken and end squareness measured with a gauge with a precision of 1 micron. The measurement must be less than the specified limit. Taking a random sample of five pellets at ‘regular intervals’ checks surface roughness. The surface roughness is measured using a proprietary gauge with a precision of 0.02 micron. Surface roughness must be within the specified limit. The frequency of the check is not stated.

PLUTONIUM CONTENT OF PELLETS

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. Inadequate mixing of the oxide powder before feeding it to the attritor 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.

A whole series 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. Without this information it is not possible to estimate the effectiveness of quality control.

The NII report implies that achieving the specified plutonium content depends on the accuracy at which the quantities of PuO2 and UO2 powders milled in the attritor are weighed. No information is provided as to how the correct weight is determined, how many personnel are involved in checking measurements, whether inputs and outputs are checked, and how a powder jam in the attritor is dealt with.

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 - again, the NII report does not say how frequently measurements are done, a crucial piece of information to judge the effectiveness of the check. 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 that plutonium particles appear as red dots.

Grain size is measured on the same samples as Pu spot size. Apparently, a polished surface of the pellet 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 polished 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 fundamentally inadequate. Assurance that the MOX fuel is therefore safe cannot be given with any confidence.

THE IMPORTANCE OF PLUTONIUM HOT SPOTS

The way in which the powder flows during the various stages of MOX pellet fabrication will determine the degree of in-homogeneity 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. Inhomogeneity of MOX fuel pellets is acknowledged in the open scientific literature to be a serious problem.

For example, 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"[11]. 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".[12]

Damage to fuel cladding is made worse by the fact that much more fission and hence more heating occurs at the surface of the pellet than at its center. 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.

INADEQUACIES OF AUTORADIOGRPHY

Alpha autoradiography is a labor-intensive method of testing a pellet for the homogeneity of Pu throughout its volume. It is destructive to the pellet and time consuming. This may account for the fact that BNFL apparently only routinely inspects a single pellet taken from about 40,000 pellets. Of the pellets inspected about 20 per cent typically fail.

Not only are very few pellets sampled but also only a thin slice is taken from a pellet for testing. We argue that, from the point of view of reactor safety, testing for homogeneity is by far the most important of all the checks. And even this one is totally inadequate in its scope. Because only a thin slice of a pellet is tested it is assumed that the result is representative of the whole pellet, this assumption is not robust.

SELLAFIELD MOX PLANT – NO SIGNIFICANT IMPROVEMENTS WITH AUTOMATION

BNFL often claim that because SMP 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 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.

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."[13]

QUALITY CONTROL AT BELGONUCLEAIRE

As described above, we do not know many details of the quality control and assurance at BNFL remain unknown. Considerably less is known about these operations at Belgonucleaire. But from the little that is known, it appears that quality control at

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[11] 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.

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

[13] Bairiot, H., van Vliet, J., Chiarelli, G., Edwards, J., Nagai, Sh., and Reshetnikov, F., 'Overview on MOX fuel fabrication achievements', 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.

Belgonucleaire is even less stringent than that at BNFL, mainly because checks are done with considerably less frequency (see table 1,) and there are fewer total checks.

Tokyo Electric Power Company (TEPCO) which received 32 assemblies of MOX fuel from Belgonucleaire in 1999 has added confusion and contradictory statements to this lack of transparency. When the falsification scandal first broke in September 1999, Tokyo Electric stated that BN had produced MOX for Fukushima-I-3 using both production lines at the PO plant. For one of these lines, an automatic laser micrometer did not cover 40% of the production line, and instead one out of every hundred is inspected manually. However, by February 2000 Tokyo Electric had changed its explanation: it claimed that all MOX produced for them had been made in one production line, which is 100% covered by automatic laser. To complicate the issue further, it has been confirmed by Tokyo Electric and the Ministry of Trade and Industry, MITI, that no data exists from the automated laser inspection, as it is overwritten, or deleted. As of March 24th, TEPCO had failed to clarify this issue, citing the commercial confidentiality of Belgonucleaire as the reason why data could not be released publicly. It may in fact not be the case that the automated fuel data is deleted, but if so, there remains the question as to why such data, important in the even of liability for example was deleted in the first place. Even BNFL did not delete their automated data on mass.

It also appears from an assessment of the graph data released by Tokyo Electric on February 24th for MOX pellets produced at BN, that the range of pellet diameter for the pellets manually inspected is too similar to be representative of a random sample.[14] The same Japanese citizens groups that challenged Kansai Electric in the Osaka District Court over BNFL falsification have now questioned this. The question arises as to whether workers at Belgonucleaire act similarly to those at BNFL, by repeatedly revolving the pellet through 90 degrees until they obtain the diameter measurement required to pass. If this is the case, the quality control process fails not only on grounds of falsification, but also on grounds of deliberate manipulation. Again only full transparency, including release of all data will answer this important question.

As far as the important check for homogeneity, there is still a great lack of clarity. The February 24th TEPCO report indicates 32 pellets selected (out of 430,000 total for Fukushima-I-3 reactor fuel) were checked for homogeneity, a slightly higher check fraction than BNFL. This may be confirmation that MIMAS technology is inferior to BNFL MOX fuel in terms of the efficiency of the blending of uranium and plutonium powders, giving rise to concern over the homogeneity of the fuel. The frequency of other tests, such as isotopic abundance and impurities (carbon, fluorine and nitrogen), is about one pellet in 20,000; hydrogen content is checked in one pellet in 420; heavy metal content in one pellet in 2,100 in practice is inadequate, oxygen to metal ratio in one in about 2,500.

It is perhaps surprising that specifications for MOX pellet quality differs between suppliers of MOX - BNFL and Belgonucleaire - for different Japanese reactors. In fact there are no agreed or consistent standards for the quality of MOX fuel. From what is known about the standard of MOX production technology, SBR versus MIMAS, as well as the frequency of quality control checks conducted by Belgonucleaire, it is highly likely that the quality of MOX fuel produced by Belgonucleaire is at least as poor as that produced by BNFL, and may be significantly worse. This has direct implications for the safe operation of Fukushima-I-3 reactor, if loading is to proceed, as well as for fuel currently awaiting shipment at Belgonucleaire, to TEPCO's Kashiwazaki-Kariwa-3 reactor.

COGEMA QUALITY CONTROL

No significant data has been released to date on the quality control standards applied by Cogema at the two operating MOX plants, Cadarache and MELLOX. Both plants produce MOX fuel for commercial light water reactors using the MIMAS process. Together with the PO plant at Dessel, the facilities are operated under the Cogema Group MOX Platform, and all of the production is marketed by Commox, 60% of which is owned by Cogema, and 40% by Belgonucleaire. The Cadarache plant operates entirely for the production of MOX fuel for German nuclear power plants, while MELLOX produces largely for French state-utility, Electricite de France. In late 1999, Cogema began production of 8 MOX fuel assemblies for KEPCO, fuel originally intended to be loaded as the second core load of MOX fuel for Takahama-4 reactor. Due to the canceling of plans to load BNFL MOX fuel, the MELLOX fuel will be the first to be loaded by KEPCO. Production of this fuel was suspended between December 27th and February 21st due to MITI concerns over quality control standards at MELLOX, but following and as yet undisclosed investigation by KEPCO, production resumed and is due to be completed during April 2000. A second batch of 8 MOX assemblies, intended for Takahama-3 is due to is manufactured at MELLOX by December 2000.

As no data has been released on quality control standards of MOX fuel produced by Cogema, it is not possible to verify whether or not the standards applied are more or less robust than those applied by BNFL or Belgonucleaire. Only release of all relevant data would provide the answer to this question. However, it is almost certainly the case that standards applied for plutonium homogeneity will not be significantly more robust than those applied at Dessel and at Sellafield. In combination with the use of the

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[14] "Reconfirmation result on quality control of MOX fuel for Fukushima-I-3 and Kashiwazaki-3", issued on February 24th, 2000, Tokyo Electric Power Company.

same MIMAS technology which produces a less homogenous uranium-plutonium mix than the SBR technology of BNFL, we have grounds for saying that Cogema produced MOX is at least as poor in quality control as BNFL, perhaps more so. Production of MOX with effective plutonium homogeneity would not be economic for Cogema to produce.

The refusal by Belgonucleaire to release off-site all quality control data for fuel produced for TEPCO (intended for Fukushima-I-3 and Kashiwizaki-Kariwa-3) raises suspicions that Cogema, as a major partner in the MOX Group Platform, is not prepared to expose its quality standards to the same public scrutiny as BNFL. Though it is worth emphasizing that BNFL only did so under intense pressure from Japanese politicians and environmental groups, which led to a demand from KEPCO and the Japanese Ministry of Trade and Industry (MITI), and then finally the UK NII. This more than raises suspicion that Cogema has something to hide. Citing commercial confidentiality may be a convenient cover, but it is not a justification, especially since BNFL, Cogema's only potential competitor, has been forced to release considerably more quality control data though still insufficient for independent analysis.

Further confirmation of the inherently poor standards of MOX quality control standards has emerged as late as March 24th, when Siemens, the fuel vendor for German reactors, confirmed that MOX fuel produced at Cadarache by Cogema contained falsified quality control data.[15] The MOX fuel was produced for the Isar-2 reactor which in total has loaded 48 assemblies from Cadarache. No MOX fuel from Belgonucleaire (or BNFL) has been loaded in Isar-2. Siemens has denied that the problem was similar to that uncovered for MOX fuel loaded in the Unterweser reactor, produced by BNFL. According to Siemens the quality control failure related to data having been not entered on the computer for 40 out of 100 pellets selected out of 7000. Siemens have now requested Cogema to assess all previous quality control data related to MOX fuel produced at Cadarache for Germany, an enormous undertaking if it is to be done thoroughly. Cogema will rightly come under significant pressure to release all relevant MOX quality control data in the following weeks.

CONCLUSIONS

As has been described, BNFL apparently applies 15 checks to its MOX pellets under the following headings: isotopic composition; plutonium enrichment; metal content; oxide/metal ratio; impurities; gas contents; appearance (visual check); outer diameter; height; dish dimension; chamfer dimension; end squareness; density; alpha-auto-radiography (to identify plutonium spots); solubility. Belgonucleaire conduct less total checks, but of a similar range, including homogeniety and diameter. No information is currently publicly disclosed by Cogema, however, we assume that similar quantity and range of checks are conducted as by Belogonucleaire.

On first sight, this appears to be a comprehensive set of checks. But in most cases the frequency of the checks is totally inadequate. In some checks only one sample is taken per 22,000 or 13,500 pellets (at BNFL and Belgonucleaire respectively - see Table 1 for details. The checks for pellet length and geometric density, for example, are done on random samples of 20 pellets per lot - that is one pellet in 200 or a sample size of 0.5 per cent. Such a low sampling rate will allow flawed pellets to get through the checking procedures, with serious implications for reactor safety and for the safeguarding and accountancy of plutonium. Of particular concern is the serious inadequacy of the checks to detect inhomogenieties in plutonium distribution in pellets. Because of the very low sampling rate, variations in plutonium homogeneity will not always be detected.

The inspection rate is clearly inadequate for a fabrication technology subject to the vagaries of powder flow. The high failure rate indicates that the inspection rate has not been defined as the minimum rate required for adequate quality control. Instead it appears to have been established by economic, rather than statistical considerations. Further, too little is known about the quality control procedures used to monitor MOX fuel pellets and rods. 'Commercial confidentiality' is used as a smoke screen to prevent independent scrutiny of quality control and quality assurance procedures for MOX. 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 behavior of plutonium and uranium in the reactor. The former has received little attention but may be at least as important as the latter.

The cost of properly checking for inhomogenieties in the distribution of plutonium in a fuel pellet, by, for example, alpha-autoradiography, would be large, from a commercial point of view prohibitively so. This is compounded by the current poor economics of the MOX industry. Available estimates suggest that MOX supply will be about two times greater than MOX demand up to the year 2015. The pressure to reduce costs in such a competitive market inevitably has impacts on the extent, and therefore effectiveness, of quality control and assurance. The margins to make substantive and required improvements may not exist for the MOX manufacturer.

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[15] Siemens press statement, March 24th, 2000.

The inability of the industry to carry out adequate checks for inhomogeneities may have serious implications for the integrity of the fuel cladding. It is extremely irresponsible of the industry to dispense with adequate quality control and assurance procedures and, in effect, rely instead on limited research trials carried out on fuel produced by different pilot fuel fabrication plants operating under optimal conditions.

In summary, we conclude that:

1. The amount of publicly available information is insufficient for any comprehensive analysis of the adequacy of quality control and quality assurance. The public therefore has to rely solely on the word of the industry and the discredited regulators. Given the furore about falsification the word of the industry is totally discredited.

2. The NII report has been limited in its scope and depth, and adds virtually no new information about quality control and assurance. The NII should be required to make adequate information available so that analysis and conclusions about the adequacy of quality control and quality assurance be made by independent analysts. Similarly the withholding of information by Belgonucleaire and Cogema, and the attitude of TEPCO is unacceptable, and disclosure of all relevant data should be immediately.

3. Of particular concern is the plutonium homogeneity of MOX pellets. It seems that autoradiography is done on only one BNFL pellet in about 22,000, and one pellet in 13,500 for Belgonucleaire produced MOX. Given the serious adverse consequences of plutonium hot spots for reactor safety, this level of frequency is inadequate and irresponsible.

4. The frequency of all BNFL and Belgonucleaire quality control checks, except the measurement of the diameter, of MOX pellets is so low as to be statistically unreliable.

5. The cost of adequate quality control and quality assurance would be high, which provides an explanation for the inadequacies of current practices. Autoradiography is particularly costly and labor intensive.

6. The evidence suggests that BNFL, Belgonucleaire, and probably Cogema use approximately the same specifications for the quality control and quality assurance of MOX pellets sold to foreign customers.

7. No significant analysis has been done by either MOX producers or regulatory bodies, such as the NII, into the implications of quality control and quality assurance for the risk of accidents when MOX fuel is used in reactors.

8. Even without the application of satisfactory quality control and quality assurance, MOX fuel is much more expensive than ordinary uranium oxide fuel. Adequate quality control and quality assurance would make it prohibitively costly.

9. Disclosures that BNFL and Cogema have produced MOX fuel with false quality control data, further confirm in our minds that adequate MOX quality control is not possible. It remains to be seen as to whether or not Belgonucleaire have also conducted falsification of MOX quality control data.

10. Quality control checks that are conducted at automated MOX production plants, specifically the yet to be opened Sellafield MOX Plant, SMP, and most likely the MELLOX plant are also inadequate to assure the quality and safety of the MOX fuel.

Given these conclusions, it is clear that MOX producers and those few utilities committed to burning MOX fuel are putting economics before safety. Given the level of information publicly provided, it is clear that MOX fuel production fails to meet the basic principles of quality control and quality assurance and that MOX fuel cannot be guaranteed safe to use.

Table-1 Frequency of BNFL and Belgonucleaire quality control checks on samples

Check type	**Frequency – BNFL (for Takahama-4 reactor fuel)**	**Frequency - Belgonucleaire (for Fukushima-I-3 reactor fuel)**
Isotopic Composition	**One pellet in 1600**	**One pellet in 20,000**
Pu Enrichment	**One pellet in 1600**	
Metal content	**One pellet in 4,000 (first lot only)**	**One pellet in 2,100**
Oxide/metal ratio	**One pellet in 22,000**	**One pellet in 2,500**
Impurities	**One pellet in 22,000**	**One in 20,000 (hydrogen one in 420)**
Gas contents	**One pellet in 22,000**	
Appearance - visual inspection	**One pellet in 12**	
Outer Diameter – manual measure	**One pellet in 20**	**One pellet in 220**
Outer Diameter – automated	**All pellets**	
Length	**One pellet in 200**	
Dish dimension – first lot after punch change	**On pellet in 700**	
End Squareness	**One pellet in 200 – first lot after pellet change**	
Density	**One pellet in 200**	
Pu spot – homogeneity	**One pellet in 22,000**	**One pellet in 13,500**
Solubility	**One pellet in 22,000**	