Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

PERFORMANCE CHARACTERISTICS AND CAPABILITY OF THE M4/12 MOX PACKAGE

A R Cory
International Nuclear Services

ABSTRACT

International Nuclear Services has completed the transport packages for the execution of Sellafield Ltd's European MOX business. Two M4/12 packages are now ready for service. The specification of the package performance had to take into account many factors. The seemingly endless permutations of the plutonium isotopic provided a challenging target to ensure a specification which would not be found wanting.

The special security requirements of the road transport system impose constraints on package weight, geometry and heat load. Customer preferences influence payload, and fuel quality criteria dictate many aspects of internal design and impose overall limits on the internal temperatures, which in turn limit the thermal rating of the package.

Ensuring the package capability is not restrictive for a considerable period into the future has required a degree of predictive reasoning more extensive than applied to packages for uranium fuels. Not only must developments in reprocessing and fuel manufacturing be anticipated, but also changes in core management at the customer power stations. Add to this that in the early stages of design no contracts were in place, and subsequently the preferences of the customer to have the flexibility to switch MOX fuel supply between different reactors - the opportunities to get things wrong were legion.

Reactor core management requirements, by pushing fuel burnup higher, result inevitably in changes to the plutonium isotopic resulting in a MOX fuel that imposes increasingly greater constraints on the shielding and thermal performance of the MOX transport package. Future developments in MOX technology could involve 'multiple-pass' cycles, where MOX fuel is reprocessed and the separated plutonium incorporated in further MOX fuel. While not considered a commercial probability at this point in time, it provides an interesting theoretical discussion with respect to the capability of the M4/12.

INTRODUCTION

The introduction of MOX fuel requires special consideration in the design and development of a suitable transport package. Previous papers have dealt with the mechanical design and construction detail of the M4/12 package entering service for International Nuclear Services. This paper looks in detail at how the underlying performance characteristics with respect to the content are established. In order to specify package performance characteristics, an understanding of the production of plutonium and its incorporation into MOX fuel is necessary, as is an understanding of the operation of a nuclear reactor.

1 FROM UO_2 TO MOX

Plutonium is evolved as a product of irradiation of uranium fuels. It represents a bi-product of the nuclear cycle which is highly toxic, has the theoretical potential for nuclear proliferation, but at the same time has a value as a potential source of nuclear fuel – mixed-oxide, or 'MOX'. Re-introduced into the reactor this helps to close the fuel cycle.

Plutonium is present in the form of a number of isotopes in the spent fuel from the reactor, and is separated as part of the commercial reprocessing operation. The isotopic composition is a function of a number of variables of the irradiation process, in other words, how the reactor is managed in terms of cyclic loading, fuel disposition in the core, and burnup. Reactor operators strive to minimise new fuel costs by maximising burnup with respect to enrichment.

However, the higher the efficiency of the reactor operating on the uranium fuel cycle, the more problematic is the utilisation of the plutonium so produced. Increasing burnup results in a lower proportion of fissile plutonium (Pu_{239} and Pu_{241}), and higher amounts of Pu_{238} (Figure 1). The latter gives rise to heat and dose which constrains the design of storage facilities for plutonium in powder form, and that of packages designed for the transport of plutonium powder, or MOX fuels. Magnox reprocessing generates plutonium with the highest content of fissile isotopes, by virtue of the low burnup of the Magnox operating cycle.

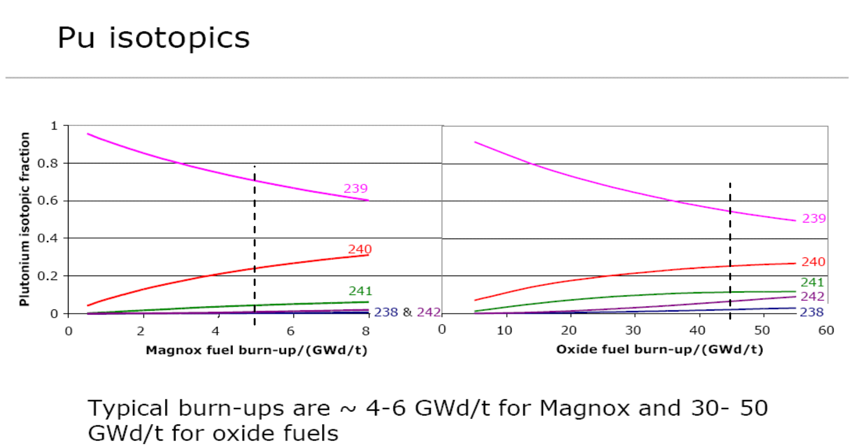

Figure 1: relationship between burnup and isotopic content

There are a number of drivers for the use of MOX fuel. Typically the use of a single MOX fuel element consumes 9kg of plutonium, and avoids the production of another 5kg. In addition to the important role in reducing the inventory of separated plutonium from commercial activities, there is demonstrated potential to incorporate weapons-grade material released by disarmament. Incorporation of ‘weapons grade’ plutonium in MOX results in ‘reactor grade’ plutonium when irradiated. Due to high levels of Pu_{238}, Pu_{240} and Pu_{242} this material is not capable of sustaining the nuclear chain reaction which is a pre-requisite for atomic weapons.

The capability to use plutonium as a fuel in MOX is useful in providing some assurance against future rises in the cost of uranium. Plutonium recycling releases energy from the conversion of the abundant U_{238} isotope into plutonium, whereas uranium fuel releases energy from U_{235}, comprising only around 0.7% of natural uranium.

Further constraints to the use of plutonium in MOX result from the short half-life of the Pu_{241} isotope (14.4 years). Considerable time may elapse between irradiation of the parent UO_2 fuel and delivery of MOX fuel. Time in the reactor cooling ponds is irrelevant as the decay product of Pu_{241}, Am_{241}, is separated out in reprocessing. However, much plutonium has been stored in oxide powder form for many years, and americium ‘ingrowth’ has become a significant factor. Am_{241} emits a gamma dose with attendant decay heat which presents an issue for effective shielding. The heat output and gamma dose of stored plutonium powder continues to increase for decades. Plutonium can be re-treated to remove americium, but this adds considerable complication and cost to MOX production. MOX fabrication facilities may impose restrictions on the acceptable level of Am_{241} according to the degree of automation, to limit dose uptake to plant operators.

2 COMMERCIAL BACKGROUND

Return of the products of reprocessing is generally a contractual requirement. In the case of separated plutonium it is an aim that, where possible, return should be in the form of MOX fuel. However, not all countries or utilities which have in the past sent spent fuel for reprocessing operate MOX-licensed reactors, or in some cases, those countries no longer have an active civil nuclear programme. In this case consideration may be made to transfer plutonium directly, or third-party burn of MOX could be agreed. Manufacture of MOX may require shipment of plutonium in oxide powder form some distance from store to MOX manufacturing facility. However, this paper concerns itself chiefly with the movement of plutonium in the form of MOX.

When planning the construction of a MOX manufacturing facility, it has to be borne in mind that the product to be made may need to be commercially viable in 15 or 20 years, hence the manufacturing route needs to incorporate sufficient flexibility to cater for increasing fissile plutonium enrichments and changing plutonium isotopic compositions over that period.

To estimate these factors with any degree of accuracy needs the maximum amount of commercial intelligence from both the operators of the power station reactors, and the designers and manufacturers of the fuel assembly components. Developments over the last 30 plus years in materials and power station management techniques have allowed fuel burnup to increase substantially, lowering the fuel component of the reactor operating costs. Fuel designers have to work on considerable lead times, but such is the competitive nature of the fuel supply business that to obtain information with any precision to help predict the need for MOX plant modifications is fraught with difficulty. ‘Best commercial guesses’ are therefore often provided by professional industry analysts and energy supply specialists.

Not only the specification of the fuels but also the quantity of required production has to be established. This requires realistic estimation on the size of the market and the prospect of penetration into it, i.e. market share, to be established.

The MOX fabrication facility then has to attune its capacity and general capability according to the best market intelligence at the time of build. However, the detailed design of the fuels themselves in terms of enrichment and overall quantities of heavy metal, are not finalised by the fuel designer until fairly close to the time when the fuel is required. The fuel designer has to take cogniscence of the reactor operating regime both historically and in terms of future intentions. MOX market capacity is to an extent determined by political considerations, depending on the energy policy of the government of the day of the destination countries. Some countries maintain a commitment to nuclear phaseout, while elsewhere there may be application of national or local policy regulating the licensing of candidate reactors for MOX fuel.

There is yet another constraint on the fuel to be manufactured, which brings us to the nucleus of this paper, the capability to deliver the fuel from the manufacturing facility to the consumer, safely and without any degradation in quality which would limit or preclude the use of the fuel in the reactor. The transport system has also to factor in complex arrangements for physical security, though this is beyond the remit of this paper.

3 TRANSPORT PACKAGE

Project timescales may dictate that the design of the transport package follows that of the MOX fabrication facility, even if ideally these should progress together. This may mean that the functional specification of the transport package can benefit, however, from more up-to-date market intelligence on fuels and reactor management. Either way, the MOX plant must produce fuel that can be transported, and the transport package must be able to transport fuel that the plant is going to produce, hence there has to be close liaison on the development of the functional specification for the package, and sufficient underpinning design and development to ensure that functional specification is met.

Goalposts may be moved by market or political constraints changing during the build process of either plant or package, or during the operating phase. Hence a strong and ongoing commitment to commercial and political intelligence gathering is necessary to best ensure commercial success and customer satisfaction. In addition to this is the necessity to keep abreast of, and respond to, regulatory change at all times.

The Transport Regulations dictate criteria which the transport package must satisfy to ensure public safety. This requires a programme of development and physical testing culminating in the preparation of a design safety report which must satisfy the

Transport Regulator. However, this may not necessarily be adequate to satisfy the customer or the fuel manufacturer that the condition of the fuel transported will be maintained in a state to ensure satisfactory performance in the reactor, hence other criteria are evolved which the package designer must address. These include the need to avoid the effects of shock and vibration during transport, for example, the avoidance of resonant frequencies which could damage fuel pins, and the need to maintain a temperature below that at which significant oxidation of the fuel pin surfaces would occur.

Security aspects of the 'Category 1' move dictate against the use of rail transport. Hence constraints are imposed on overall package weight that are much more restrictive than spent fuel or waste packages. The activity of the contents, and linked to this the dose rate and dose spectrum, is much lower than for a spent fuel package, and advantage is taken of this in the design of the package shielding. The most significant part of this is lightweight hydrogenous material to shield the neutron dose. This helps to optimise package weight and allow a useful payload within the constraints of the road regulations.

As the MOX fabrication facility progresses with contractual and technical arrangements for fuel manufacture, a clear understanding must exist of the capabilities of the transport package. Due to the number of variables (isotopics, cooling time, mass, enrichment) a close liaison between the package Design Authority and the plant production management is essential at this time to avoid the potential for embarrassment with either customer or regulator.

Figure 1: M4/12 MOX package (less shock absorbers)

4 'HEADROOM'

This is the margin between the normal operating conditions and the maximum capability of the package. A well-specified package will operate with a small positive headroom when required to transport the most demanding payload. Conversely a package which runs out of 'life' as payload demands ratchet upwards is symptomatic of an unsound projection of business demand. A package operating with too large a headroom is clearly over-specified, or over-designed.

As an initial estimate, a lead can be taken from the specification for the fuel manufacturing facility, in terms of, say, bounding isotopics and enrichment. However, this may have been established in a necessarily conservative manner at an earlier period when less certainty of future reactor operations or fuel design existed, and opportunity may be appropriate to refine, or close down some of the assumptions.

Market intelligence is a very valuable factor, and knowledgeable input from fuel manufacturing and nuclear generation is invaluable.

Table 1: Performance characteristics of M4/12 package

	PWR	BWR
Payload, fuel assemblies	4	12
Thermal capacity, W	3200	3200
Pu fissile enrichment, w/o	6.25	7.45
Maximum total activity, A_2	5.87E+06	7.27E+06

Plutonium isotopics arising from spent fuel are known at the time of receipt of the spent fuel for reprocessing. Whereas the MOX fabrication plant has to be capable of handling the extremes from a point of view of dose uptake to operators and process capability, the opportunity to blend batches may give scope for a less demanding specification to be appropriate to the transport package, and hence less wasted headroom. Typically plutonium incorporation into MOX fuel may be 5-10 years after separation, hence for the initial years of the package's life the requirement can be confidently established.

Enrichment is a rather different issue. The economics of nuclear generation require the maximising of burnup with respect to enrichment, which minimises the fuel requirement. Burnup limits are generally set by fuel cladding metallurgy, but have advanced from around 30GWd/tU towards 50GWd/tU or even higher, over the last 30-or so years. This conflicts with the requirement to reduce the plutonium stockpile as rapidly as possible, as it would seem the less efficient reactors offer the best prospects as 'MOX burners'. In any case, MOX transports can be reduced by increasing the fissile plutonium enrichment within the bounds of the capability of the reactor to handle it.

As an example, a PWR operating at 40GWd/tU burnup could make a directly proportional reduction in the number of MOX assemblies required per year if burnup was increased to 50GWd/tU, but the plutonium consumption could be maintained by a proportional *increase* in the plutonium fissile enrichment. Hence package design requires an anticipation of such reactor trends. Increase of fissile enrichment in the fuel carried increases reactivity and consequently reduces criticality margins.

An additional consequence of the trend towards high burnup is the nature of the plutonium isotopics of the spent fuel generated. High burnup equates to high levels of Pu_{238} which is the main heat generator and gamma dose source. The resultant plutonium characteristics are likely to provide the most challenging criteria to transport as MOX fuel, and consequently may require a limit to be placed on the enrichment to ensure package decay heat loads are moderated and fuel quality ensured. There is a tendency to grade plutonium in terms of 'quality' – the higher quality relating to higher levels of Pu_{239} and low levels of Pu_{238}, as characterised by plutonium produced from Magnox reprocessing. Lower 'quality' plutonium is the product of high burnup spent fuel or – even more so - from spent MOX fuel.

Some theoretical work has been carried out to study the number of times MOX fuel can be recycled. The limiting issues involve the degradation of the plutonium isotopic; to maintain an equivalent fuel assembly from the reactor operating point of view requires a successive increase in the plutonium fissile enrichment – whereas the same isotopic degradation increases heat and dose requiring the transport package to *reduce* the enrichment to maintain decay heat within design limits. This conflicting requirement would limit the use of the M4/12 package in respect of multiple-pass MOX – but whether this ever becomes a commercial reality is highly questionable.

Package capability with respect to the Package Design Safety Case is determined before the fuel assemblies are manufactured. Drawings and data sheets for the fuel assembly must be available to determine the mass of the assembly, the length, diameter and cladding thickness of the pins, and a pin 'map' showing the disposition and enrichment of the pins in the array. The weight of heavy metal (uranium and plutonium) in the assembly is required. On top of this, the isotopics of the plutonium batches should be known. This enables a specific assessment to be made of the activity and decay heat for the proposed shipment. This in turn can be used to derive temperatures of the fuel pins in transport and satisfy the customer and fuel vendor that those temperatures remain below the level where fuel quality could be considered an issue.

Table 2. Example of input/output data for package / proposed fuel assessment

MOX FUEL DECAY CALCULATION					
FUEL REFERENCE:		Type G			
PACKAGE REFERENCE:		Package M			
Input data:			**Output data:**	assembly	package
Data reference date:		2007	activity at reference date, Bq	1.14E+16	4.56E+16
Transport date:		2010	activity at transport date, Bq	9.99E+15	4.00E+16
Weight of HM per assembly, kg:		405.8	A2 at transport date	8.25E+05	3.30E+06
Average Puf w/o per assembly:		4.78	decay heat W, trans. date	6.03E+02	2.41E+03
No. of assemblies per package:		4	Wt of (Pu+Am), kg	30.28	
Radionuclide composition % Pu wt:			Wt of Pu.fiss (inc Am241), kg	19.40	
Batch AA-01	Pu238	2.55	Pu separation date	2004.8	
	Pu239	54.09			
	Pu240	26.11			
	Pu241	9.32			
	Pu242	7.50			
	Am241	1.03			

There are a number of pertinent points to note in the preparation of the safety case and licensing of the MOX package. Normally a certificate of Approval issued by the competent authority will specify a limit of activity, in Becquerels. This is inappropriate for a MOX package, as while the activity declines with age of the plutonium, the A_2 value increases with age. Hence it has been adopted as UK practice to specify a limit to the derived A_2.

Coupled with this are the rise in dose rates and heat load with ageing fuel – which continue for decades after plutonium separation. Hence the package capability must be determined on the basis of the 'oldest' plutonium which is intended to be incorporated in the MOX. This is the converse of the norm established for spent fuel and highly-active waste packages.

The flowsheet (Figure 3) illustrates the complexity of the inter-relationships between the reactor, MOX fabrication facility and the design, specification and licensing of the transport package.

CONCLUSION

Knowledge of reactor operation and management, fuel design and future trends have been applied to the functional specification and design of the M4/12 MOX transport package operated by International Nuclear Services. The package capability has been demonstrated by a combination of test and analysis to meet all anticipated present and future requirements of Sellafield Ltd MOX programme. Additionally the capability of the package has been explored beyond the current operational horizon, and a good understanding of operational constraints gained.

REFERENCES

[1] Plutonium Management in the Medium Term (OECD/NEA Working Party, 2003)
[2] 'Plutonium' - Nuclear Issues Briefing Paper 18 (Uranium Information Centre, June 2005)
[3] 'Plutonium' – Information Brief (World Nuclear Association, September 2006)

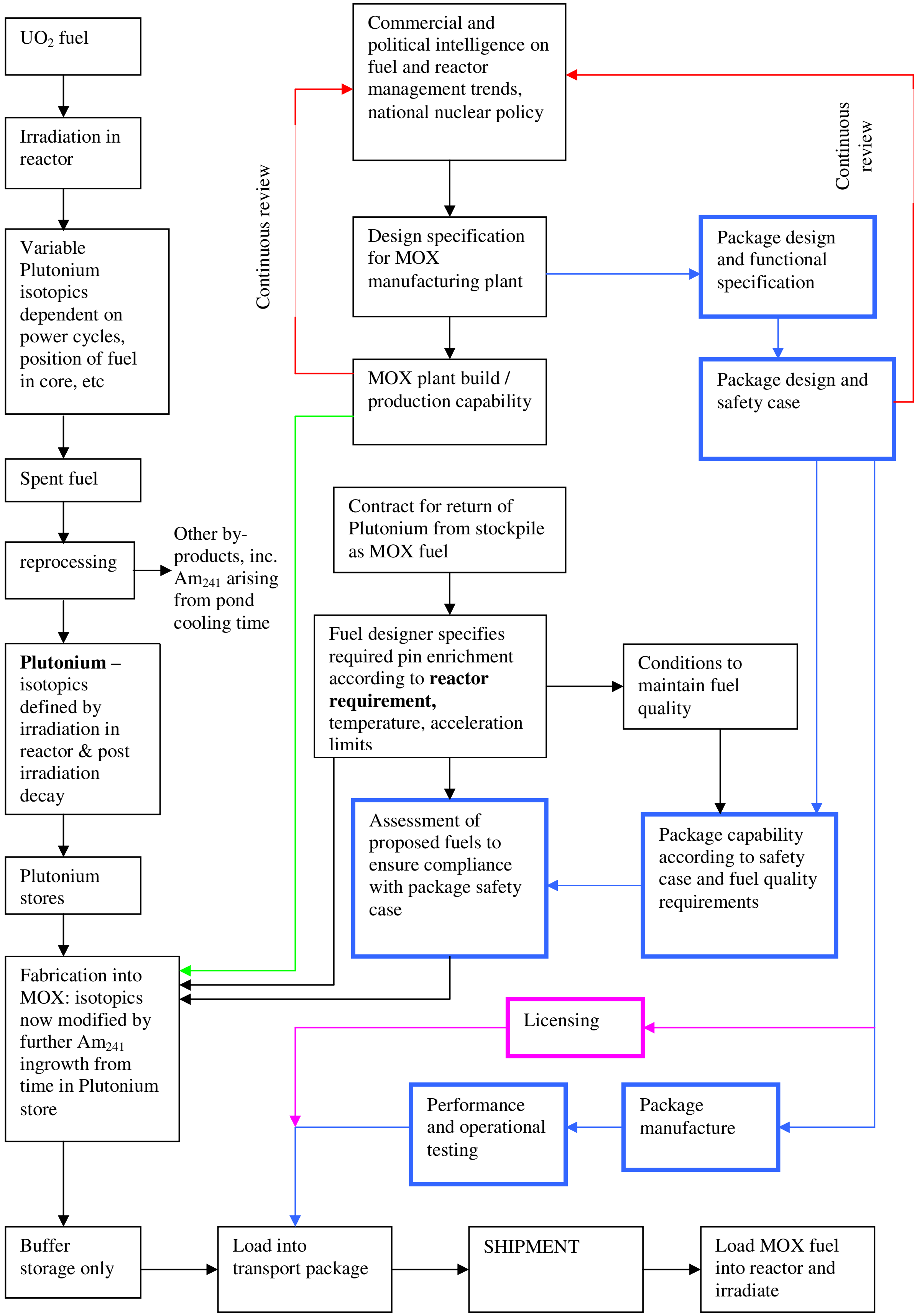

Figure 3: MOX transport package and MOX process route