Advanced Fuel Cycle Cost Basis Report: Module D1-2

LWR Pelletized MOX Fuel Fabrication

Nuclear Fuel Cycle and Supply Chain

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	All	**Version of AFC-CBR in which Module first appeared:** 2004 AFC (Shropshire, et al 2004) as Module D1-2
	2020	All	**Latest version of module from which new technical data was used to establish unit cost ranges:** 2020
		All	**New technical/cost data which has recently become available and will benefit next revision:** • Progress in Japan on construction of JMOX plant in Rokkasho-mura. • UK reports on possibility of new MOX plant to process their large, separated Pu stockpile.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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ACRONYMS

ACFAC	A Cash Flow Analysis Code
AFC-CBR	Advanced Fuel Cycle Cost Basis Report
AFCI	Advanced Fuel Cycle Initiative (DOE-NE)
Am	americium
ANL	Argonne National Laboratory
ANS	American Nuclear Society
ASTM	American Society for Testing and Materials
BN	Russian acronym for fast reactors
BNFL	British Nuclear Fuels Limited
BWR	boiling water reactors
CAT	category (safeguards and security)
Cm	curium
CPI	Consumer Price Index
D&D	Decontamination and Decommissioning
DF	Decontamination factor (in reprocessing plant)
DOE-NE	Department of Energy-Nuclear Energy
DU	depleted uranium
DUF6	depleted uranium hexafluoride
DUO2	depleted uranium dioxide (aka DUOX)
DU3O8	depleted tri-uranium octoxide
EOL	end-of-life
EPRI	Electric Power Research Institute
ES&H	environmental, health & safety
EU	enriched uranium
EUO2	enriched uranium dioxide (aka EUOX)
FC	fuel cycle
FCRD	Fuel Cycle Research and Development
FOAK	first-of-a-kind
FR	fast reactor
FTE	full-time equivalent
G4-ECONS	Generation IV- EXCEL Calculation of Nuclear Systems
G&A	general and administrative
GB	glovebox

GE	General Electric
HM	heavy metal
HVAC	heating and ventilation, and air conditioning
IAEA	International Atomic Energy Agency
IDC	interest during construction
IPD	implicit price deflator
JNC	Japan Nuclear Corporation
J-MOX	Japanese MOX facility
Kg	kilograms
LCC	life cycle cost
LEU	Low-enriched uranium
LEUO2	low enriched uranium dioxide (aka LEUOX)
LWR	light water reactor
MELOX	French MOX facility
MeV	million electron volts
MFFF	MOX Fuel Fabrication Facility at Savannah River (cancelled)
MIT	Massachusetts Institute of Technology
MOX	mixed oxide
MPC&A	materials protection, control and accountability
MTHM	metric tons of heavy metal
MTU	metric tons of U
N/A	not applicable or not available
NAC	Nuclear Assurance Corporation
NASAP	Non-proliferation assessment systems analysis program
NEA	Nuclear Energy Agency (part of OECD)
NEI	Nuclear Energy Institute (USA)
NFS	Nuclear Fuel Services, Corp (BWXT subsidiary)
NASAP	non-proliferation assessment systems analysis program
NNSA	National Nuclear Security Administration
NOAK	Nth-of-a-kind
Np	neptunium
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (USA)
O&M	Operations & Maintenance
OECD	Organization for Economic Cooperation and Development

OMB	Office of Management and Budget (USA)
ORNL	Oak Ridge National Laboratory
PB	process building
PR	preface
PCCI	Power Capital Cost Index
PDCF	Pit Dismantlement and Conversion Facility
PHWR	pressurized heavy water reactor
PNNL	Pacific Northwest National Laboratory
PRISM	Power Reactor Inherently Safe Module (GE fast reactor concept)
PUREX	plutonium and uranium recovery by extraction (reprocessing method)
PWR	pressurized water reactors
QA	Quality Assurance
QC	Quality Control
REPU	re-enriched reprocessed uranium
RFP	request for proposals
RO/CM	remote operations/contact maintenance (glovebox)
RO/RM	remote operations/remote maintenance (gloveboxes with add'l shielding)
RU	reprocessed uranium (aka REPU)
SA&I	Systems Analysis and Integration (part of DOE-NE-FCRD)
SC	South Carolina
SMP	Sellafield MOX Plant (UK)
SNF	spent nuclear fuel
SRS	Savannah River Site (USA)
SWU	separative work unit
Tl	thallium
Th	thorium
TM	technical memorandum
TVA	Tennessee Valley Authority (USA)
TCC	total, financing inclusive capital cost
TRU	transuranic
U	uranium
UK	United Kingdom
UOX	uranium dioxide (aka UO2)
UREX	uranium extraction (reprocessing method)
USAEC	United States Atomic Energy Commission

USNRC	U.S. Nuclear Regulatory Commission
VIPAC	vibrocompacted fuel
V-LEU	“virgin” LEU (never irradiated)
VVER	vod-vodyanoi energitichetsky reactor (Russian version of PWR)
WG	weapons grade (Pu)
WIPP	Waste Isolation Pilot Plant (USA)
WIT	what-it-takes
WNA	World Nuclear Association
WSB	Waste Solidification Building (SRS)
Zr	zirconium

Module D1-2

LWR Pelletized MOX Fuel Fabrication

D1-2.1. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2021 Update:** FY 2020
- **Nature of this 2021 Module update from previous AFC-CBRs:** Use of U,Pu MOX life cycle cost data from late 1970s Non-proliferation Assessment Systems Analysis Program (NASAP). This archived data has been updated in 2018-2019 to reflect today's regulatory and economic conditions and is presented in 2017$. For the lower unit cost MOX fabrication case the PuO2 from the reprocessed LWR SNF is assumed to be fabricated immediately after aqueous PUREX reprocessing, thus minimizing the time for undesirable actinide radioisotopes, from the standpoint of radiation safety, to build in. Fabricated MOX utilizing separated and multi-year stored Pu from aqueously reprocessed SNF has also been added to this Module as a second LWR MOX fabrication variant, requiring additional and more costly glovebox design and operations to protect personnel. This new NASAP-informed data augments historical data and unit cost projections appearing in the 2009 (Shropshire et al 2009), 2012 (Dixon et al 2012), and 2017 Dixon et al 2017) AFC-CBRs. The "What-it-takes" 2017$ unit fabrication cost values based on the updated NASAP studies are escalated to 2020$ for this 2021 Update Report.
- **Estimating Methodology for latest (2020 AFC-CBR) technical update from which this 2020 update was revised:** The NASAP LWR MOX life cycle costs were ultimately derived from a bottom-up life cycle cost estimate prepared for a "reference" ~500 MTHM/yr 1970s vintage CAT-III PWR-UOX plant. NASAP staff added the floor space, machinery, gloveboxes, and other equipment that would be needed to transition the UOX design to a U,Pu MOX "subject" plant design (what would now be a CAT-I facility). FCRD-SA&I staff (authors of this report) then adjusted some of the civil costs to reflect today's more stringent regulations concerning safety and security. Escalation factors appropriate to each life cycle cost category were than applied to go from 1978$ to 2017$. The G4-ECONS life cycle cost levelization algorithms were then used to calculate a constant-dollar unit fabrication cost for 50 years of assumed plant operations. (The methodology for transitioning from the "reference" UOX plant to other fuel types is described in detail in new Module D1-PR.).

D1-2.1.1 BASIC INFORMATION

Industry Interest. Industry interest in the use of LWR MOX fuel peaked in the 1960s and 1970s when it appeared that uranium shortages would force the recycle of both the partially burned uranium and the fissile plutonium formed by U-238 neutron absorption during LWR UOX fuel irradiation. Projected high uranium prices suggested that a partially closed fuel cycle utilizing one or more passes of MOX fuel would yield economic benefits when compared to the one through UOX fuel cycle. Very large MOX fuel fabrication facilities in the 300 to 2000 MTHM capacity plus a large LWR SNF aqueous reprocessing industry were envisioned. With low uranium ore prices today the overall fuel cycle cost economic incentive has largely disappeared, and relatively few countries are pursuing partial recycle with MOX. A recent publication by Geoff Rothwell (Rothwell 2014) contains a detailed analysis that suggests MOX will not be needed until U-ore prices rise and the unit cost of reprocessing LWR SNF falls considerably. It is also noted that any new MOX fabrication facilities are likely to be much smaller, up to 200 MTHM/yr, than predicted in the 1960s and 1970s. A good technical summary of worldwide MOX experience appears in (Cowell and Fisher 1999), a document prepared before the US began its MOX program designed to utilize surplus weapons grade plutonium.

Module D1-2 LWR Pelletized MOX Fuel Fabrication

Fuel Form. An LWR MOX fuel assembly with its array of pellet-loaded rods appears identical to a $LEUO_2$ thermal LWR fuel assembly. In fact, for the European reactors that burn MOX fuel, the two types of assemblies reside together in the reactor, with 1/3 MOX: 2/3 LEUOX being a typical fuel assembly loading ratio. Even the ceramic MOX pellets within the rods appear nearly identical to their ceramic LEUOX counterparts. It is because of the radiotoxicity of plutonium; however, that vastly different types of plant designs are needed to fabricate MOX fuel. This is true even though 90+% of the MOX feed material flowing through the fabrication plant is the depleted, natural, or slightly enriched U-235 assay UO_2 (aka UOX) diluent that is blended with the 10% or less (by mass) of PuO_2 powder to form the MOX pellet. Most of the world's MOX fuel is presently fed to PWRs, mainly in Europe and Japan.

Status of Industry Outside the US. European industries, such as Cogema (now ORANO), Belgonucleaire, BNFL,and Siemens/ALKEM, have successfully fabricated LWR-MOX, and European utilities in France, Switzerland, and Belgium have been successfully burning it for over a decade. The PuO_2 in all of this European MOX arises from the reprocessing of spent $LEUO_2$ thermal reactor fuel (UOX-SNF) at facilities such as LaHague in France and formerly THORP in the United Kingdom. The Japanese have begun use of MOX in their reactors as part of their "Pluthermal Fuels" program and are constructing a MOX facility at Rokkasho-Mura slated for possible startup in 2024 (WNN 2020) . Japan has also produced MOX at a small PNC facility in Tokai. The UK has stopped producing MOX, but the SMP (Sellafield MOX Plant) has not yet been decommissioned. (Platts 2007a and World Nuclear News 2011).

Status of Industry Inside the US. Up until 1978, the U.S. was on the verge of using MOX as part of a partially-closed LWR fuel cycle. A MOX fabrication plant design had already been submitted to the USNRC for licensing review for a MOX plant at Anderson, South Carolina, with PuO_2 to come from a nearly completed PUREX-based fuel reprocessing plant at nearby Barnwell, South Carolina. Construction was never started on the Anderson MOX Facility. The empty concrete shell for the Barnwell Reprocessing Plant still sits near the Savannah River Site in SC. All this Pu recycle activity was halted by the Presidential Edict of Jimmy Carter putting an end to plutonium recycle because of nonproliferation concerns with spent fuel recycling. In 1993, after the end of the Cold War, the U.S. began to start investigating the use of MOX fuel derived from surplus weapons-grade plutonium (WG-Pu). Reports by the National Academy of Sciences (National Academy of Sciences 1995) and others (ORNL 1996; Williams 1999) documented the technical and economic feasibility of utilizing existing U.S. utility LWRs to burn partial cores of weapons-derived MOX fuel. In 1996, a Record of Decision (U.S. DOE 1997) was issued by DOE to pursue the MOX reactor option as one of two methods to disposition plutonium. In 1997, a procurement action was started to find a corporate entity willing to design, construct, and operate a government-owned MOX Fuel Fabrication Facility (MFFF) at the USDOE/NNSA Savannah River Site (SRS). In early 1999, the consortium Duke, Cogema, Stone, and Webster (DCS – now Shaw AREVA MOX Services) was chosen for this purpose and was also chosen to expedite the burning the MOX fuel at Duke Energy's two PWR reactor sites, McGuire and Catawba, just north and south, respectively, of Charlotte, North Carolina. (These MOX use contracts have now expired and MOX Services unsuccessfully tried renegotiating with Duke and other potential customers for MOX fuel contracts. These negotiations failed since the SRS-MFFF completion and start-up date appeared to be too far in the future.) By 2012 the design of this plant was complete, NRC construction approval had been received (NTI 2007) and in 2015 construction was still underway despite NNSA's decision to proceed with another Pu disposition technology [Construction was still underway due to SC Congressional delegation inserting federal funding. DOE-NNSA never plans to use it and is pursuing an alternate method (dilute and geologically dispose in WIPP) for Pu disposition]. The plant was to have processed 70 to 100 MTHM per year for over 10 years. The intent was to disposition 34 MT of weapons-grade plutonium over this campaign and possibly some other less-pure government plutonium scrap. As will be explained in status paragraphs below, the reactor-based US Pu disposition program and the MFFF construction program have both been entirely terminated as of July 2021.

Status of Industry in Russia. Prior to 2007 (Platts 2007b) a similar, US-funded "build-to-print" LWR-MOX plant, also based on French MELOX technology, was being designed for a parallel Russian program at Tomsk (Seversk) in Siberia. The MOX was to be burned in Russian VVER-type pressurized-water reactors. Liability, funding technology transfer, and now political concerns have prevented that LWR-MOX project from proceeding any further. The Russian Pu-disposition program now utilizes weapons-derived fast reactor MOX in BN-type fast reactors for their Pu-disposition program (Platts 2007b). They are presently operating a small fast reactor MOX fabrication facility at Zhelesnogorsk Mining and Chemical Combine.

Generic Comments on Reactor-based Disposition of Weapons-derived Plutonium. Figure D1-2.1 shows a flowsheet for a generic reactor-based plutonium disposition program.

For weapons-derived MOX use, the cost savings were to have been realized by not requiring perpetual government storage and guarding of separated plutonium and the fact that other less-developed plutonium-disposition methods, such as immobilization in fission product laden glass, are likely to increase costs and encounter technical difficulties. MOX was essentially to have been made available to the utilities by DOE at a unit cost somewhat below that for energy-equivalent LEUO_2 (UOX) fuel assemblies in order to provide an incentive to U.S. electric utility participation. USDOE/National Nuclear Security Administration (NNSA) plans were to have limited the U.S. plant (SRS-MFFF) to weapons plutonium-disposition activities only, even if the plant life was limited to only 10 to 12 years of operations. U.S. policy generally still continues to discourage plutonium recycle and the construction of commercial recycling facilities for UOX-SNF, such as MOX fabrication or reprocessing plants

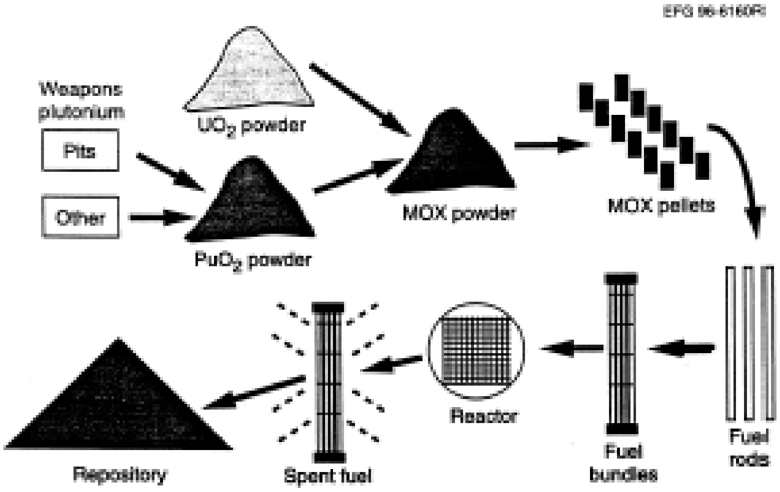


Figure D1-2.1. Generic reactor-based option for weapons plutonium-disposition (ORNL 1996).

Basic Information Update Status from Previous Updates to AFC-CBD.

This information from previous versions of the AFC-CBR is provided to give the reader some historical context as to how MOX deployment and ultimately MOX unit cost estimates for MOX fabrication have evolved, especially in the USA,

2012-2017 Updates: Little had changed from the *December 2009 Advanced Fuel Cycle Cost Basis Report* (Shropshire et al 2009) in the areas of the basic industrial process for MOX fabrication and its interfaces to other fuel cycle steps; there have been, however, a few changes in the status of some of the world's MOX fabrication facilities (This historical information augments in detail the more generic MOX deployment information in the Section above.)

- The Sellafield (United Kingdom) MOX Plant (SMP) is in the process of shutting down and will be slated for eventual decommissioning. Its major customers were Japanese utilities which are now facing the prospect of shuttered reactors after the March 2011 tsunami-induced Fukushima event. The SMP only realized a fraction of its design production rate of 120 MTHM/yr and only operated for a few years. The UK is still considering the burning of MOX fuel in new Generation III+ LWRs as a method of dispositioning its large stockpile of over 110 MT of separated Pu from its commercial and military reactor programs (Nature News and Comment 2011). A new and larger plant would be required that might also be able to produce MOX fuel for fast reactors. (Module D1-4). The UK is considering the fast reactor as part of its future Pu-disposition and energy strategy and is evaluating the GE-Hitachi PRISM fast reactor design.

- The status of the 130 MTHM/yr J-MOX plant at Rokkasho-Mura is unclear. It began construction in 2010; however, the Fukushima event may spell the end of the Japanese "pluthermal" MOX burning program. At the time of drafting this 2021 Update Report (August 2021) construction of the J-MOX facility continues but at a slow pace.
- The French MELOX facility continues to operate successfully and has a capacity of 195 MTHM/yr. **Error! Reference source not found.** shows a photograph of this facility located in Marcoule, France.

Figure D1-2.2. MELOX LWR-MOX Fuel Fabrication Facility in France (ORANO 2021).

- The U.S. MOX Fuel Fabrication Facility (MFFF) is still under construction (over 70% complete in 2012) at the USDOE Savannah River, South Carolina, Site. It has been beset with rising projected costs and schedule slippage (Augusta Chronicle 2012). **This plant is <u>not</u> designed (from a worker protection and non-proliferation policy standpoint) to take as feed separated commercial reactor Pu, which has higher concentrations of americium, neptunium, and Pu isotopes other than Pu-239**. MFFF's feedstock comes from military programs, thus a special "aqueous polishing" front end is needed to remove weapons-related impurities and prepare a pure PuO_2 powder suitable for glovebox MOX fabrication. Another predecessor step is required to render the weapons form or "pit" into feed appropriate for the aqueous polishing from end. This step will also have to be integrated into the MFFF front end and in other SRS facilities and with additional high cost. A waste packaging facility (Waste Solidification Building [WSB]) is also to be constructed at SRS to handle the TRU waste, (Author's note: By 2016 the WSB had been cancelled. Until 2016 the MFFF was anticipated to make MOX fuel for both PWRs and BWRs. Although limited MFFF construction had been ongoing, the NNSA in 2016 presumed it would never be completed or operated, and that a "dilute and dispose" process involving geologic disposal at the U.S. WIPP (Waste Isolation Pilot Plant) will be utilized for weapons-grade Pu disposition)
- As part of the Year 2000 Joint U.S-Russia Plutonium Management and Disposition Agreement (PMDA) (U.S. Dept of State 2000) both the U.S and Russia had originally agreed to burn excess weapons Pu in their LWRs (called VVERs in Russia). By 2010 Russia had decided to burn their Pu in sodium-cooled fast reactors of the BN-800 variety. The type of fuel is likely to be pelletized SFR MOX (Module D1-4) or SFR VIPAC fuel (Module D1-5). The PMDA was modified in 2010 to reflect this new reality. The Russian Federation recently (2016) formally pulled out of the PMDA agreement due to worsening relations with the U.S.; however, they are already using WG-Pu in their BN-800 fast reactors (WNN 2021). The U.S. has not formally pulled out of the agreement; however, the intent to terminate the MFFF Program essentially negates the PMDA intent to produce (by irradiation in reactors) isotopically altered Pu not suitable for weapons and also self-protecting due to built-in fission product radioisotopes. (Author's note to above history: As of July 2021 the MFFF program has been entirely terminated and the 70+% complete MFFF building at SRS slated for other defense-related programs. A "dilute and dispose" program has been initiated for which the ultimate destination of the surplus WG-Pu will be the Waste Isolation Pilot Plant (WIPP) in New Mexico.)

Projected costs for some of these facilities in the bullets above will be discussed in Section D1-2.1.4 below.

D1-2.1.2 FUNCTIONAL AND OPERATIONAL DESCRIPTION

MOX Fuel Fabrication Process. The steps involved in the fabrication of MOX fuel are basically the same as those for LEU fuel assembly production except that most of the front and middle process steps must be enclosed in gloveboxes to protect the workers from exposure to radiotoxic plutonium compounds. A MOX plant is also a CAT-I facility from the standpoint of safely and security, hence more stringent and costly regulations apply. The radioactivity level in a MOX plant is also somewhat higher than for UO_2 because of the high alpha-specific activity of most Pu isotopes and in addition, spontaneous neutrons, beta, and gamma radiation emanating from the decay of plutonium isotopes and of their daughter radionuclides. Some radiation also comes from (alpha, n) reactions where PuO_2 is in contact with low atomic weight materials. Fire protection considerations are also important with pyrophoric plutonium compounds, and process areas within the process building must be capable of isolation. There also are security and material accountability considerations (Category I) arising from the fact that MOX has a proliferation or terrorist attractiveness level much higher than for $LEUO_2$. This is because plutonium could be readily chemically separated from the uranium in the MOX and has great value as a fissile material for a nuclear weapon. This fact requires that the stringent Materials, Protection, Control, and Accounting (MPC&A) and safeguards be implemented and that the process building itself be extremely robust and resistant to attack or intrusion. In the US a Safeguards and Security Category I facility is required. The avoidance of nuclear criticality is also more of a consideration for MOX due to the smaller critical mass of Pu-239 as compared to U-235. All these considerations contribute to the much higher capital and operating costs for MOX as compared to CAT-III LEU, however, realistic economics must be evaluated on the whole nuclear fuel cycle, where for commercial MOX use, reduced ore, conversion, and SWU costs and waste disposal cost savings due to reprocessing in tandem with MOX use may become evident. A 1987 NEA report, *Plutonium Fuel: An Assessment* (NEA 1987) presents several such analyses and sensitivity studies in detail.

D1-2.1.3 PICTURES AND DIAGRAMS

Error! Reference source not found. shows the generic MOX production process for either commercial (Pu-239 isotopic content less than 94%) or weapons-derived (Pu-239 content 94% or greater) MOX. The powder feedstocks PuO_2 and DUO_2 are blended into a 20 to 30% plutonium “master-mix” powder, which is then later blended with more DUO_2 to the desired fissile content of 4 to 9% plutonium in heavy metal. Because of criticality concerns, all early processing operations are in small batches of a few kilograms Pu each. Final blended MOX batches may be 100 kg MOX or more. The pellet pressing, sintering, grinding/finishing, and inspection operations are nearly identical to their LEU counterparts except for the difficulty of handling somewhat smaller batches and the need for glovebox operations. Once the pellets are loaded into the Zircalloy tubes and the tubes are welded and cleaned, the decontaminated rods in most cases can be direct contact handled outside a glovebox.

The bundle assembly area is very similar to that of the LEUOX plant, however pelletization and rod loading will require more floor area because of the need for very large gloveboxes and their HVAC and maintenance systems. Because of the higher radiation field arising from decay of americium-241, a plutonium-239 decay daughter, it is necessary to limit worker exposure times to MOX fuel assemblies. Pu-236 decay products such as U-232, Spontaneous neutron generation and alpha-n reactions also contribute to the worker dose. As will be explained below, the timing of MOX fabrication after SNF reprocessing is very important in relation to worker exposures and the need for more glovebox shielding.

D1-2.1.4 MODULE INTERFACES

Impurity Considerations in the Separated PuO2 required for U,Pu MOX Fabrication. For today’s PUREX-based reprocessing schemes for LWR SNF PuO2 powder is the product produced after separations and then packaged at the reprocessing facility. If the separations and solidification processes therein have high decontamination factors (DFs) the PuO2 produced is considered “clean” from the standpoint of being amenable to safe handling in standard alpha-emitter-containing gloveboxes. If the PuO2 is stored for several years (2 or more) before fabrication into MOX there is a build-in of actinide isotopes that are significant gamma emitters and pose unacceptable radiation fields for glovebox workers (Beer. Schiedel & Riedel 1982). In this case more robust and expensive shielded gloveboxes and more complex maintenance equipment is required or an additional “aqueous” or “electrolytic” separation process is needed to purify the Pu (Alwin et al 2007 and GAO 1992). The same requirements would be true if the reprocessing facility has lower DF separation of Pu from higher actinides and fission products, in which case small, but radiologically significant, amounts of certain fission products and higher actinides such as neptunium, americium, and curium would be carried over into the PuO2 product. A conclusion that can be drawn from this is that even if the PuO2 is produced by a high-DF reprocessing facility, it is best to fabricate the PuO2 product into MOX as soon as possible. (France has enough powerplant reactor customers that they can do this.) Having to store plutonium also has significant costs, even if stored at the reprocessing plant. If this is not possible an actinide storage facility will be required along with significant life cycle costs. These storage costs are discussed in AFC-CBR Module E. If aqueous polishing of “old” PuO2 is required, it would probably take place at the actinide storage facility, where significant additional costs estimated at $10 to $28/gram of Pu (in 1989$) would be required (NEA 1989).

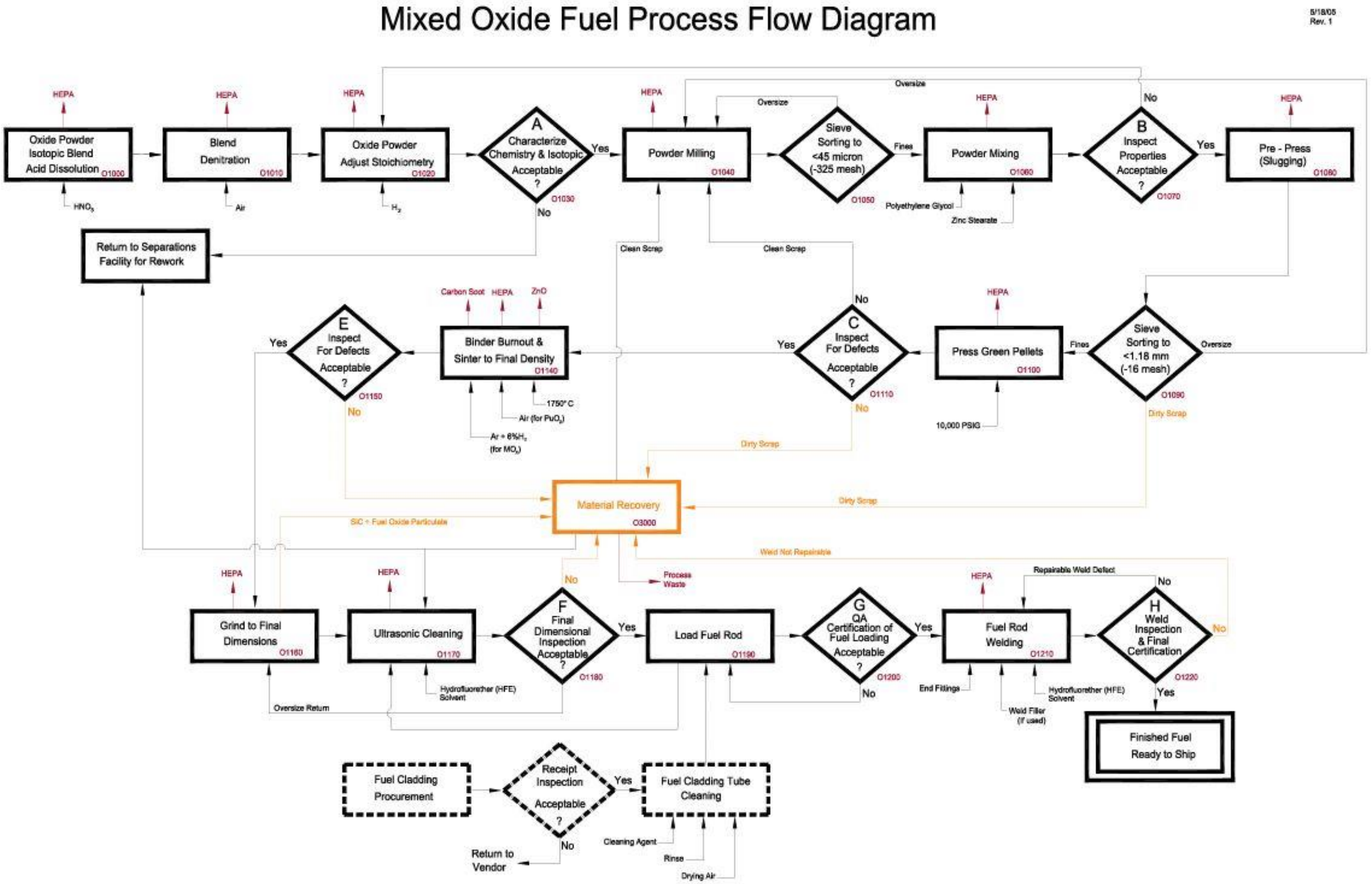


Figure D1-2.3. Generic MOX fuel process flow diagram (DOE-AFCI Fuels Working Group, 2007).

It is useful to understand how these detrimental “build-in” radionuclides arise. According to NEA data (NEA 1989) when LWR fuel is discharged the ~1% of Pu in the SNF has the following isotopic vector (Table D1-2-1) for UOX PWR fuel burned to 53 GWd/MTHM):

Table D1-2-1. Typical Discharge Pu Isotopic Vector for PWR SNF at 53 GWd/MTHM*

Pu-236	20 ppm
Pu-238	2.74%
Pu-239	50.37%
Pu-240	24.15%
Pu-241	15.16%
Pu-242	7.06%
Am-241 from Pu-241 decay	5100 ppm

* U-232 not derived from Pu-236 decay is present in SNF in part-per-billion quantities. Its decay chain also adds to the gamma dose.

The trace Pu-236 with a half-life of 2.8 yrs has a decay product of U-232, which has a 69 yr half-life. This U-232 decays via 1.9 yr half-life Th-228 to Tl-208 which emits a very potent 2.6 MeV gamma ray upon decay. Am-241 is produced by beta decay from the more abundant Pu-241 which has a 14.4 yr half-life. Am-241 decays to Np-237 via a 5.486 MeV alpha particle and a weak 0.06 MeV gamma. Together these gamma emitters are the “build-in” radioisotopes which pose a hazard to personnel and require additional glovebox shielding and other protective measures. Once the LWR-SNF is reprocessed, the separations process removes most of the built-in U-232 and Am-241; however, the isotopics of the Pu are not altered. The whole process of decay begins again as soon as the separated Pu -bearing solution is processed to an oxide for storage or, hopefully, for immediate fabrication into MOX fuel.

Front-end Interfaces. For commercial MOX as done in Europe, the starting materials are reactor grade PuO_2 powder arising from aqueous PUREX-type reprocessing such as is done at LaHague or THORP. The reactor-qualified powder so produced is stored, preferentially for less than two years before fabrication, in special double-walled cans in protected storage areas at the reprocessing plant. (Costs related to MOX are assumed to start with shipping of this powder in special double-walled cans and special “safe and secure” trucks from the reprocessing plant to the MOX fabrication plant). The diluent natural, depleted, or slightly enriched UO_2 powder, which is the largest HM fraction of the MOX mix, must also be reactor-spec grade (ASTM-2002) and is usually purchased from or manufactured by uranium converters or fuel fabricators with aqueous processing equipment, although some dry-process UO_2 powder is being qualified for MOX use. (Slightly enriched [$0.0071 <$ U-235 assay (mass fraction) <0.015] uranium diluent would be likely to be reprocessed uranium oxide, most likely recovered in the same reprocessing facility as the plutonium oxide. Module K2 discusses worker dose issues associated with reprocessed uranium [REPU] refabrication.) This UO_2 material can be shipped by normal commercial trucks in sealed drums. Diluent uranium oxide powders can be produced in Safeguards and Security Category III facilities, which are the least regulated of the three security categories I, II, and III.

The front end steps for the U.S. and Russian plutonium-disposition projects were more complex, a complicating fact that partially led to the demise of the US Program. The metal plutonium pits and any other weapons-grade legacy plutonium forms from the DOE complex must be converted to clean reactor spec PuO_2 (ASTM-2002). For the U.S. program, a Pit Disassembly and Conversion Facility (PDCF) had been planned at SRS to oxidize the impure plutonium metal to impure PuO_2. This “pit-derived” impure PuO_2 plus other legacy impure PuO_2 is then stripped of its gallium, americium, uranium, halide, and other impurities in an aqueous-polishing front end step: i.e., an MFFF- aqueous polish (AP building) addition to the overall SRS-MFFF MP (MOX Fabrication Process building). From this AP point onward, the commercial MOX and Pu disposition flowsheets are basically the same, with the back-end of the SRS-MFFF (called the MFFF-MP) being very similar to the French MELOX fuel fabrication plant at

Marcoule. Prior to program termination the SRS-MFFF had planned to use DUO_2 (DUOX) as the diluent, thus reducing the U-235 content and maximizing the Pu-239 content of the fissile part of the MOX fuel. This reactor grade DUO_2 must be manufactured by a deconversion plant starting with clean USDOE legacy DUF_6 , supplied in large, 14-ton cylinders which are located at one of the former U.S. gaseous diffusion enrichment plant sites. Shaw-AREVA MOX Services, the DOE/National Nuclear Security Administration plutonium disposition contractor, had been responsible for implementing this conversion step and had subcontracted Framatome-ANP to use a specially modified (for DU use) deconversion line at their Richland, Washington LEU fuel fabrication plant to test the basic deconversion process. Shaw-Areva and the DOE Savannah River had been developing a procurement process to obtain the ~1000 MTU of depleted material diluent needed for 34 MT Pu MFFF operations. The cost of this uranium conversion step was to be included in the SRS-MFFF operations costs and was likely to have cost in the tens of dollars per kilogram of DU deconverted, with the actual unit cost depending on the batch sizes and quality and morphology of the UO_2 powder required. Framatome had already prepared cost proposals to Shaw-Areva MOX Services for this operation; however, DOE's ultimate choice of the DUO_2 provider will have depended heavily on economics and the response to the procurement request for proposals (RFP). All of the plans described above are now moot due to NNSA's decision to change WG-Pu disposition options; however, the descriptive material above has been included since many of the technical and cost issues associated with reactor-based WG-Pu disposition, such as separated Pu impurity removal and uranium diluent supply, are germane to any MOX Program.

Back-end and Other Interfaces. Storage and shipping of the finished MOX fuel assemblies to the reactor is included in the cost. Special safe and secure transport vehicles are needed for this purpose. For the U.S. plutonium-disposition program the DOE/National Nuclear Security Administration was to have provided this secure transportation service.

Transuranic and low-level waste from the MOX fabrication plant must also be handled. For the U.S. disposition program, waste was to have been processed and packaged by modified existing SRS waste facilities plus a new facility, the Waste Solidification Building (WSB). Because the plutonium arises from the weapons program, transuranic waste containers can be sent to the DOE/National Nuclear Security Administration's Waste Isolation Pilot Plant (WIPP) geologic disposal site near Carlsbad, New Mexico. For future commercial MOX facilities in the U.S., use of the Waste Isolation Pilot Plant may not be possible, since WIPP's legislated mission is for defense-related Government programs. MOX production wastes would have to be jointly considered along with reprocessing wastes and a viable disposal option studied and implemented. AFC-CBR Fuel Cycle Modules J, L, and I discuss some possible waste disposal methods.

Discharged MOX SNF fuel assemblies would be handled in the same manner as discharged UOX fuel assemblies, with at-reactor pool storage followed by dry cask storage or packaging for shipment to a reprocessing facility.

D1-2.1.5 SCALING CONSIDERATIONS

Scaling rules are similar to those for LWR fuel production, since the fuel manufacturing is performed in parallel process lines. The line size is limited by the fact that many of the process steps are batch operations with batch size limited by criticality concerns. Capacity additions to a plant would likely be realized by adding shifts or adding a new line in an existing building. In fact, from Table D1-2-2 that shows two representations of the known costs for existing facilities, one for construction (top) and one unit cost for all life cycle elements (bottom), it is difficult to notice any highly definitive capital construction cost scaling relationship. Because the fixed safety, security, and other infrastructure costs associated with both the capital and operating costs are generally high for MOX fabrication facilities, the unit costs climb rapidly as throughput decreases. In fact, according to Stoll (Stoll 2002) there is such a relationship for unit costs, which include capital and operating components, as shown in Figure D1-2-4. Therefore, for MOX to be more competitive, large throughput plants should be built. Rothwell discusses

MOX economy-of-scale issues in (Rothwell 2015). Scaling information for multiple fuel types based on the late 1970s NASAP study (ORNL 1979a) will be presented later in this report.

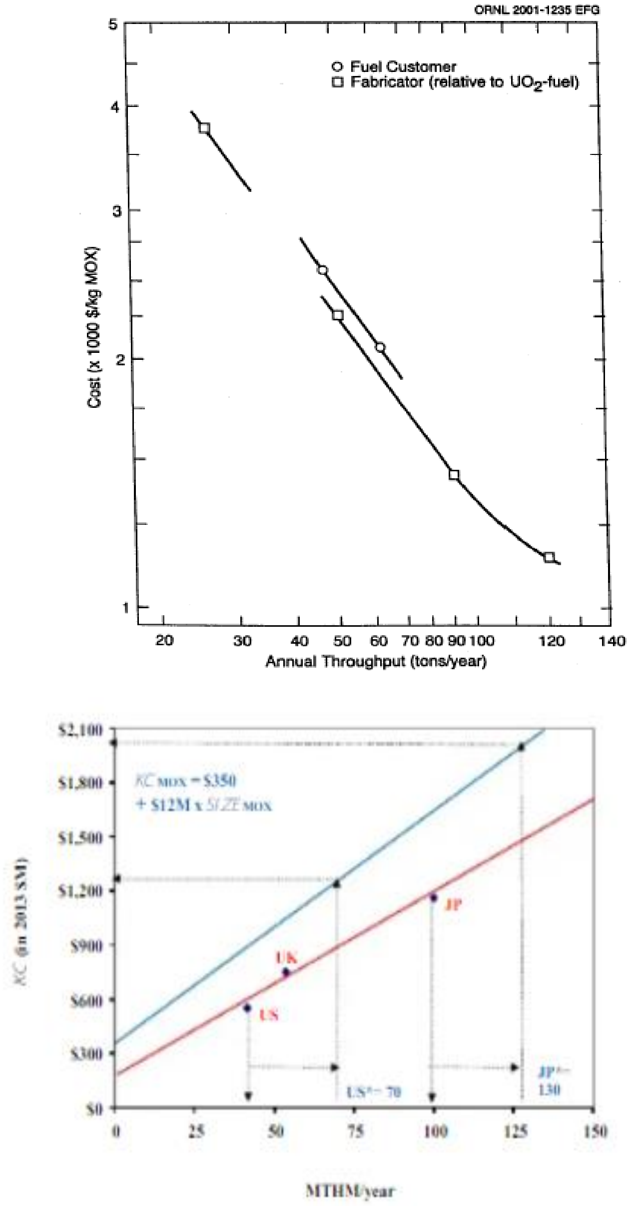


Figure D1-2.4. MOX unit cost and MOX capital construction costs as a function of throughput (top figure: Stoll 2002) and (upper line on lower figure: Rothwell 2015).

D1-2.1.6 COST BASES, ASSUMPTIONS, AND DATA SOURCES

D1-2-1.1 Costs Based on Historical and Literature Data

Most of the MOX fuel fabrication cost data available are for existing facilities in Europe, although no detailed life cycle cost data were found for the French MELOX or the Belgonuclaire facilities. Bunn, et al. 2003 performed a comprehensive survey of life-cycle cost information. Table D1-2-1\2 summarizes this information along with the Section D1-2 authors' analysis, described below, of the U.S. SRS-MFFF projected life-cycle costs in 2009, when the analysis was performed. [Note: the expected year 2017 cost and schedule for the now cancelled SRS MOX plant (aka MFFF) had ballooned to several times that year 2009 amount, according to the most recent press information (Mufson 2017)]. Each of the studies in the table below provides the construction costs, (in the form of overnight cost) and occasionally the operation and maintenance costs. In order to generate a levelized unit cost (in $/kgHM), however, it is necessary to make assumptions on the discount rates for capital recovery and on the facilities' expected lifetimes. A common set of assumptions applied here are described in the bullet list below. (Note: For consistency, the same set of assumptions on discount rates and facility lifetimes are also applied to the analyses performed in the other contact-handling D1 modules and in remote handling module F2/D2).

- **Facility lifetimes of 50 years:** These types of facilities are designed with a high degree of redundancy and reliability, and they could therefore be operated for a long time. However, several MOX facilities in the past were closed after just a few decades of operations, generally for political or commercial reasons, and therefore an expected lifetime based purely on technical factors has not been determined yet. A reasonable analogy could be made with fuel fabrication plants for commercial UOX: For example, the South Columbia Westinghouse fabrication plant was commissioned in 1969, is currently producing without serious technical or political issues and there are no known plans for its shutdown, thus providing a representative example with a proven lifetime of 52 years as of this writing, and probably several more years, if not decades, of expected future operations. Other nuclear facilities, such as reactors, have received U.S. NRC licenses for life extension of up to 60 years, and other types of chemical plants, such as refineries, have been in operations for more than a century. Fifty years was chosen here as representative of a "long lifetime", until more specific data becomes available or if licensing regulations are changed.
- **Discount rate of 3%**: It was chosen here as representative of a FY 2017 discount rate that would be appropriate for a government project or a commercial project with a government-guaranteed financing. According to Section 8 of Office of Management and Budget (OMB) Circular A94, which specifies which discount rates should be used for government projects, the treasury borrowing rates (currently about 3%) should be used for discounting if performing "cost-effectiveness analyses". "Cost effectiveness analysis", defined in Section 5, bullet b, of OMB Circular A94, could include various types of reprocessing facilities, under the assumption that the objective is to compare alternative ways to achieve the same benefits to society (such as for example a lower waste heat and volume after reprocessing), and it is impractical to consider the dollar value of those benefits.

In the following, each facility of Table D1-2-2 is analyzed in detail.

The UK BNFL SMP plant was completed in 1997 but started operations in 2001, and it was later revealed that the planned acquisition of German expertise in MOX fabrication did not materialize as planned, and instead the completion of the plant relied on limited in-house expertise. Eventually it produced only small quantities of usable MOX fuel, about 14 MT in its entire lifetime instead of the planned 120 MT/y (Brady, 2013). The German Hanau-2 plant was 95% constructed but never operated (supp. ref: Nuclear Monitor, 1994) so it is difficult to say for sure if the specifications would have been met with the reported costs. However, it is also noted that the Hanau-2 plant was constructed on the same site of a previously operational MOX fabrication facility that operated successfully for several decades, albeit at a much smaller scale. It is conceivable, therefore, that the Hanau-2 facility could build on the experience of Hanau 1, thus reducing the chances of failure. Both Hanau plants have been decommissioned.

Table D1-2-2. Available data on MOX fuel fabrication plants.

Plant	Owner	Location	Capacity (MTHM/yr)	Financing	Capital Cost (2003$)	Operating Costs (2003$)	Ref
SMP (shut down)	BNFL	Sellafield UK	120	Private & Gov't	750M	50M	Bunn et al., 2003
Hanau-2 (never operated, decommissioned)	Siemens	Hanau, Germany	120	Private	750M	Not avail	Bunn et al., 2003
J-MOX: Rokkasho (under constr)	JNC	Rokkasho-mura, Japan	130	Private & Gov't	1,000M	Not avail	Bunn et al., 2003
SRS-MFFF (partially constructed but never operated)	DOE/NNSA	Aiken, So Carolina U.S.	70	Gov't	3.9B not incl aqueous polish (AP)	220M/yr not incl AP	Trade press staffing and TPC scaled for capacity and function
SRS-MFFF (under constr)	DOE/NNSA	Aiken, So. Carolina U.S.	70	Gov't	4,800 incl AP	$275M/yr	Trade press staffing and TPC

The Total Project Costs of the US Savannah River MOX Fuel Fabrication Facility (MFFF) was estimated for the 2009 CBR utilizing the expected cost at the time, and adjusting the costs numbers by (1) removing duplicated scope for administration and other support buildings and by (2) adjusting to the scope of a MOX fuel fabrication facility that uses all of the product produced by an 800MT/yr LWR reprocessing center. Consequently, an un-adjusted and an adjusted unit costs were provided in the 2009 CBR based on the expected cost of the MFFF facility. However, those estimates are now obsolete and new, substantially increased estimates, have been provided. (Supp. ref: The State, 2016) reports a new revised estimate of $17B as of September 2016. The original budget in 1999 was $620 million, with a 2006 starting date: in 2017 it appears that the project was still about 10 years from the start. (Supp. ref: Mufson 2017)

The total construction cost in 2007 for MFFF was estimated at $4.8B, adjusted for the factors discussed above in the 2009 CBR to a range of $4.0B to $5.1B with levels of contingency ranging from 10% to 40%. O&M costs were calculated in CBR 2009 starting from available staffing levels, and fractions for other O&M costs such as utilities (20%), miscellaneous materials (15%), 3% for insurance and other miscellaneous small projects and $100M for the specialized fuel fabrication hardware costs. This yielded a point estimate of $275M/yr. Without aqueous polishing, the staffing was expected to be reduced to about 700 and the annual operating costs drop to $220/yr. These annual amounts are respectively 6% and 7.5% of the initial capital investment, in line with the range of 4% to 7% reported by (Bunn 2016) for radiochemical facilities.

With an annual capacity of 70 MT/y, a 50 year facility lifetime and 3% discount rates, the adjusted unit cost ranges based on the CBR 2009 estimates are between 2200 $/kgHM and 2800 $/kgHM for capital costs, and between 3100 $/kgHM and 3900 $/kgHM for O&M. Total unit cost for MFFF, based on the CBR 2009 adjusted costs are therefore between 5300 \$/kgHM and 6700 \$/kgHM. Substantially higher values would be calculated for the 2016-revised capital cost of \$17B.

In conclusion, the MFFF project appears to have been a victim of typical "first-of-a-kind" and "altered scope" problems and also mismanaged, with a construction cost (from Table D1-2-1) several times that of other existing and under construction facilities for MOX fabrication. The reasons for the escalating costs are complex (Mason 2015),and will not be discussed here. However, the U.S. DOE-NNSA found in a report released in December 2016 that "The contractor lacked the fiduciary will to plan and execute work to fully benefit the project and taxpayer" (supp. ref: Mufson, 2017). Therefore, this facility appears to not be representative of the cost of a well-executed construction project for MOX fabrication. **For these reasons, the cost estimates of the MFFF will not be included in the expected cost of a MOX fabrication facility as assessed in this module.** The summary costs will instead be based on the other 3 facilities for which cost data are at least partially available: the SMP, the Hanau, and the Rokkasho MOX facilities.

Regarding O&M costs, the two values of \$220-\$275 M/y for SRS-MFFF were reported in (the 2009 Cost Basis Report). The operational cost of SMP was reported in (Bunn, 2003), at about \$50 M/y, or 7% of the initial investment costs. No information was found on the O&M costs of the Hanau-2 facility, but it is noted that the SMP data, with O&M costs of 7% of overnight construction costs, may be a reasonable assumption to make also for the identically-sized Hanau-2. It is noted that typical ranges for reprocessing facilities were found in (Bunn 2016) to be between 4% & 7%.

The O&M cost of Rokkasho MOX was not reported in Table D1-2-1 from (Shropshire et al 2009). However, subsequent data found in 2010 (Suzuki 2010) increased the total construction cost for the Rokkasho MOX facility from \$1B to \$2B, and reported a total project cost of \$12.5B. With a facility lifetime of 40 years (Suzuki 2010) and no discounting for the expenditures in different years during the operational life of the plant, the annual O&M costs would be \$263M, or 13.2% of the initial capital investment. This value is substantially higher than the typical range of 4% to 7% for other radiochemical facilities (Bunn 2016). While an explanation for this value was not found, it could be speculated that it could be due to a higher cost of labor in Japan as compared to U.S. and European countries.

The unit costs (in \$/kgHM of fabricated fuel) for the fabrication of MOX fuel, based on the costs reported in Table D1-2-2, are shown in Table D1-2-3, for 3 different assumptions about discount rates and facility lifetimes. For the unit costs' "low value" for Rokkasho provided in Table D1-2-2, it was assumed that the O&M cost would be 7% of the construction cost, while for the "high value" the expected 13.2% annual O&M cost from (Suzuki 2010) was utilized. The low, medium and high values for both SMP and Hanau-2 have different assumptions on discount rates and facility lifetimes, from long lifetimes (50 years) with low discount rates for the "low value" to short lifetimes (30 years) and commercial discount rates for the "high value".

Table D1-2-3. Unit cost of MOX fuel fabrication based on the expected cost of various existing (SMP and Hanau-2) and under construction (JNC Rokkasho and SRS MFFF) facilities, for 3 different assumptions about discount rates and facility lifetimes.

Facility	Low cost (3%, 50y) (\$/kgHM)	Higher cost (5%, 40y) (\$/kgHM)	Highest cost (10%, 30y) (\$/kgHM)
SMP (BNFL)	658	778	1074
Hanau-2 Germany (Siemens)	658	778	1074
JNC Rokkasho Mura, Japan [a]	1122	1425	2672

a. Expected completion in mid-2019 (World Nuclear News 2015)

It is observed from Table D1-2-2 that MOX fabrication unit costs are between 650 $/kgHM and 1000 $/kgHM for both SMP and Hanau, under a range of assumptions on discount rates and facility lifetimes. Rokkasho has higher unit costs, but the facility experienced a substantial amount of cost overruns, due to various factors that will not be discussed here. However, because of this, it is observed that this facility, similarly to the MFFF albeit to a lesser degree, is a poor representation of a well-executed construction project for a MOX fabrication facility. Consequently, the costs derived from this facility are likely to overestimate the unit costs that could be expected from a well-executed construction project.

The average of the 2017$ costs of the 3 facilities are $813/kgHM, $993/kgHM, and $1606/kgHM, approximated as $800/kgHM, $1000/kgHM, and $1600/kgHM. These unit costs are recommended for the triangular distribution of the expected cost of pelletized MOX glove box fabrication for LWR MOX fuel.

Unit costs from various literature sources

Table D1-2-4 shows the range of unit production costs for LWR MOX fuel gleaned from the literature. The range is very large and is influenced by market and political factors in addition to pure engineering economics.

Table D1-2-4. Unit fabrication costs for LWR MOX fuels as proposed by various literature sources.

Reference/Date	**Fabrication Cost in $/kgHM ("then year $")** **L=Low; M=Medium or Reference; H=High**
Bunn et al., 2003	(L/M/H) 700/1,500/2,300
OECD NEA, 1994	(L/M/H) 800/1,100/1,400
Delene et al., 2000	(L/M/H) 2,000/3,200/4,000
CFTC analysis of SRS MOX FFF publicly available data	(L/H) 3,400/ 4,700 (aqueous polish of weapons-derived feed excluded)
NEA 2001	(L/M/H) 1,000/1,250/1,500
NEA 1989	(L/H) 700/1000
MIT Future of Nuclear Fuel Cycle 2003	(M) 1500
MIT Future of Nuclear Fuel Cycle 2009	(M) 2400
MIT Future of Nuclear Fuel Cycle (MIT 2011)	(M) 2400
Red Impact 2006	(M) 1800
Rothwell 2015	(L/H) 2345/3185
WISE Nuclear Fuel Cost Calculator (WISE 2009)	(M) 1840
DEC 2009 AFC-CBR (Shropshire et al 2009)	(L/M/H) 3,000/3,200/5,000
(EPRI 2009)	(L/M/H) 750/1,250/1,750

D1-2.1.7 PWR MOX FABRICATION COSTS-BASED ON DETAILED LIFE CYCLE COST DATA FROM WHAT IS NEARLY A COMPLETE "BOTTOM-UP" ESTIMATE FROM

THE LATE 1970s NASAP FUEL CYCLE ANALYSIS PROGRAM

D1-2-1.2 Base Estimating Assumptions.

The 1977-1980 Non-proliferation Assessment Systems Analysis Program (NASAP) effort had among its many objectives the one of costing multiple fuel types on a consistent comparative $/kgHM basis. The reference facility is a 520 MTHM/yr UOX (ceramic pelletized UO2) fabrication facility for which a conceptual, bottom-up estimate (ORNL 1979) was prepared for all major life cycle cost elements and for which a unit cost was calculated in constant year 1978 US dollars per kgU (or kgHM for U,Pu fuels). This reference UOX facility is the basis from which life cycle costs for other fuel types, such as PWR U,Pu MOX, and SFR U,Pu MOX were developed. The engineers in ORNL's Metal and Ceramics Division examined a reference UOX plant design in detail and asked the following: "What changes would need to be made to a hypothetical CAT-III UOX facility and its operations to enable it to produce a similar amount (in terms of MTHM/yr) of other fuel types using a two-process line design philosophy. Although the original design calculations, bills of material, and cost estimator's log sheets could not be found in the ORNL NASAP archives, it was apparent from the depth and quality of the published reports (ORNL 1979a, 1979b and 1979c) that considerable care had been taken in defining the changes in equipment type, building space and type, staffing requirements, and consumables needs required to go from totally hands-on fabricated UOX (CAT-III) to more complex fuel types such as CAT-I PWR or SFR MOX and their requirement for more radiotoxic feed materials, such as separated Pu. Regulatory issues at the time were well understood, since an NRC-licensed MOX facility was being designed for location in Anderson SC. This plant was to utilize the PuO2 produced by planned reprocessing of ~30,000 MWd/MTU LWR spent fuel at the nearly completed Barnwell facility near the Savannah River Site in South Carolina. The NASAP engineers and analysts had to address the following technical and institutional factors in going from production of CAT-III UOX to CAT-I MOX: (Note that in 1979 the regulatory terms CAT-I through CAT-III were not used. We add them since they are now used to highlight major design requirement differences in US nuclear facilities.)

- Contact handling and maintenance would require nearly all front-end process operations to be conducted in gloveboxes (Glovebox handling is still considered "contact" handling in contrast to totally remote handling using robotics and manipulators through very thick windows).
- Gloveboxes and their gas handling and HVAC systems would require a larger footprint (single-story square footage) than for the UOX building
- The EUF6 to EUO2 conversion step at the front of the UOX process would need to be replaced by a powder preparation and blending step for the PuO2 and UO2 (depleted, natural, or reprocessed U) feed materials
- The much higher number of Curies in a MOX plant vis-à-vis a UOX plant requires construction of a more robust process building capable of containing internal fires, withstanding destructive natural phenomena, and deterring outside security threats. The cost per square foot for the MOX process building will be higher than for the UOX process building. MOX requires a USNRC Security Category I facility as opposed to a Category III facility for UOX for U-235 at 4.95% or less.
- Quality assurance requirements for a more complex blended fuel such as MOX are more difficult to achieve than for UOX. A different ASTM Standard (ASTM 2002) for MOX powder applies.
- Health physics considerations, criticality considerations, security considerations, and quality control considerations for MOX vis-à-vis UOX require more staff, hence higher annual recurring costs.
- Decontamination and decommissioning of a more radioactive MOX facility and its contaminated equipment will incur greater costs.

In this subsection a side-by-side comparison of life cycle cost elements for both PWR UOX and PWR MOX will be provided. It should be noted that the same type of comparisons would apply to BWR UOX and BWR MOX fuel because of the similarity of the material content and process steps to those for PWR fuels. The technical rationale for cost changes will also be discussed.

The PWR MOX plant described in NASAP document ORNL/TM-6501 (ORNL 1979) has the following characteristics as defined by the ORNL NASAP assessment team:

- The plant is an Nth-of-a-kind (NOAK), high-throughput facility assumed to be constructed in 5 years and operated successfully for at least 20 years. (The NASAP authors assume a 20-year life in their capital recovery calculation. Realistically the plant should continue operating after the capital is "written-off". Two $/kgHM unit costs of fabrication would result: a higher one which includes the 20 years of capital recovery, and a lower one for the remaining "operations only" years for which only recurring costs are included.)
- It has an average production rate of 480 MTHM/yr (already adjusted for 70% capacity factor). This compares to 520 MTHM/yr for the UOX plant. The designers made the ~8% throughput reduction for the MOX plant so that the two-process line philosophy could be maintained with a more complex process. Compared to today's largest existing MOX plant, the French MELOX facility at 195 MTHM/yr, the hypothetical NASAP plant is very large. The 520 MTHM/yr hypothetical UOX plant from which it is derived; however, is small in throughput compared to UOX-only plants such as the Westinghouse South Columbia (SC) UOX Fabrication Plant at 1100 MTHM/yr. In the mid-1970s the US nuclear power deployment plan was to quickly move toward recycle of both plutonium and reprocessed uranium in partially closed LWR and eventually totally closed SFR breeder fuel cycles. It was also assumed that reactor designers would move quickly toward the implementation of full MOX cores in LWRs. The subject 480 MTHM/yr MOX plant could provide reloads for 22 full MOX LWRs at 1978 PWR performance conditions (lower burnup and lower capacity factor than today's NPPs).
- The fuel assembly hardware, design, and appearance are identical to the PWR-UOX fuel assembly. The elemental heavy metal content of a PWR fuel assembly is 460 kg for both UOX and MOX.
- The plutonium content is 3.5% Pu (of which 75% is the thermally fissile isotope Pu-239) in total heavy metal with the Pu separated by an aqueous PUREX reprocessing scheme from relatively low burnup (~30,000 MW(th)-days/MTHM) PWR spent fuel. This burnup is low compared to today's MOX designs requiring 6 to 10% Pu coming from the reprocessing of higher burnup LWR fuel (>50,000 MW(th)-days/MTHM) with a higher fractional content of non-Pu-239 Pu isotopes that do not fission well in a thermal neutron system. This difference is due to the fact that the NASAP study was done in 1978 when LWR refuelings occurred more often (annually) than those today (18 months to 2 years), and LWR capacity factors were lower (<80%) compared to over 90% today. Fuel design and quality improvements have also allowed higher burnups today.
- PuO2 and UO2 powders meeting the ASTM fuel specifications (ASTM 2002 and successive standards) are provided to the facility. Conversion of UF6 (depleted, natural, or low-assay reprocessed material) is required to provide the UO2 diluent that constitutes 96.5% of the MOX fuel. This UF6 deconversion step was assumed to be conducted elsewhere, and the cost in 1978$ would be on the order of 8 to 20 $/kgU for fuel grade UO2 powder. The unit fabrication cost does not include this conversion cost or the uranium or plutonium source material costs of the feed materials. Fuel fabrication is a "value-added" service rather than a nuclear material cost.
- The following three financing scenarios were analyzed by the NASAP report authors: Government financing, normal risk private sector industrial financing, and high-risk private sector industrial financing. The high interest rates of the late 1970's era were assumed.

The next few paragraphs will show how the NASAP document authors transitioned the UOX facility to a MOX facility, including required technical changes, radiation safety and other regulation-imposed changes, and their cost consequences. All cost changes in the tables to be presented below are in constant 1978 dollars, with the escalation to 2017$ and other changes corresponding to the 2017 regulatory and macroeconomic environment to be presented in a later subsection. A later subsection will also present how the levelized unit fabrication cost (in 2017 US$) is calculated in a manner conforming to the G4-ECONS methodology developed by the CBR authors specifically for use in the Cost Basis Report. (Note that the original draft of this report was prepared in FY2018, hence the use of 2017 US$. Inflation indices such as the Implicit Price Deflator or Consumer Price Index can be used to calculate unit costs in later years $)

The first step was to lay out the UOX fabrication process equipment and auxiliaries onto a process floor or "footprint" for a single-story building. The engineers performing this layout task used sizing and cost information from vendors for items such as pellet presses, sintering furnaces, grinders, tube handlers, and automatic welders. The basic fabrication process is essentially the one described in Module D1-1 for a two-process line plant, with each line capable of handling ~ 250 MTHM (or MTU) annually. Table D1-2-5 lists the various manufacturing steps and the area required for each. The floor areas in the process building required for process support activities such as quality assurance and maintenance are also included, with the total CAT-III UOX process building totaling 100,000 square ft. The cost of the UOX building structure, including the heating, ventilating, and air conditioning (HVAC) system, but no process equipment, was assumed at $200/ft2 in year 1978 constant $ for most areas of the process building. Because the UOX process building contains fluorine compounds and low-enriched uranium compounds, it had to be more robust than most standard industrial building structures of its time. (As discussed later, it would not, however, have met all of today's tighter hazard protection and nuclear material security requirements.) This 1978 UOX structure would have been more expensive than the conventional and typical steel girder, insulated sheet steel wall and roof industrial construction ("Butler Building") prevalent then and now for most non-nuclear manufacturing operations. Table D1-2-5 shows a total process building cost of $21.4M in 1978 USD.

The next step by the NASAP analysts was to populate the UOX building with the chemical and metallurgical process equipment. Table D1-2-6 lists the 1978 USD cost of the equipment needed in each process area. The engineers preparing the estimate worked from equipment lists based on a process flowsheet. They obtained equipment vendor price quotes for major items such as pellet presses and sintering furnaces. (The equipment list and vendor quotes were not included in the technical documentation (ORNL/TM reports, ORNL 1979, 1979a 1979b and 1979c) published by the Metals and Ceramics (M&C) Division at ORNL. This Module's author recently inquired with a long-time retired M&C Division staff member on whether the ORNL working files were archived. Apparently the needed funding and professional staff were not available to archive or otherwise preserve this data at the termination of the NASAP effort. The equipment costs were tabulated using the same cost accounting categories as the process building areas in which the equipment would reside. Table D1-2-6 shows a total UOX equipment cost of $34.1M in 1978$.

In order to obtain a process building and equipment estimate for a CAT-I MOX facility, the NASAP analysts performed the following transitional steps:

- Estimated the additional area needed for each process step based on the consideration that many process steps would need to be contained in gloveboxes and serviced by a more complex glovebox fire protection, radiation detection, and negative pressure glovebox ventilation system.
- Replaced the first UOX process step (EUF6 to EUO2 conversion) with a first step for MOX (blending of UO2 and PuO2 powders).
- Increased the unit cost ($/ft2) for most areas of the process building because of the higher cost of nuclear-safety grade filtered ventilation systems servicing the gloveboxes and the higher cost of a structurally more-robust building capable of withstanding fire and natural phenomena events (earthquakes, hurricanes, floods, and tornadoes) and providing high protection of nuclear material

assets. Radiation protection of personnel would become a driver in the design of the building also, especially in the design of the HVAC system. All of this is driven by the radiotoxicity of plutonium and its orders-of-magnitude higher specific activity vis-à-vis low enriched uranium. (Note that the individual glovebox costs are under "equipment" rather than "process building" [civil structure] costs.)

- Most process equipment had to be redesigned for operation and maintenance inside gloveboxes. Contact handling and maintenance via gloves was the design philosophy. End-process steps (after pellets are sealed in tubes) could accommodate direct manual handling with precautions taken for personnel radiation exposure from higher transuranic isotopes. "Influence factors" based on fuel designs were utilized by the NASAP analysts for this transition process.
- Cost estimates were prepared for the gloveboxes, their atmosphere control systems, the equipment within, and the costs of installing and testing this equipment. The costs of considerably more health physics related equipment are also included. These costs were tabulated using the same cost accounting structure as the process building areas.
- A NASAP MOX fabrication case designated "RO/RM" (remote operations/remote maintenance) was developed for the greater glovebox shielding and more remote maintenance required for fuels fabricated from separated Pu where trace HA or FP contaminants are present or Pu-236 or Pu-241 daughters have had time to build in. "Clean" Pu was assumed fabricated in the NASAP-designated "RO/CM" (remote operations/contact maintenance) case which has less glovebox shielding. The radiation threshold data from transition from one case (RO/CM) to the other (RO/RM) was not available in the NASAP documents. The life cycle costs for the "greater glovebox shielding case (NASAP Case # (U,Pu)O2 "RO/RM") will appear in a later section of this report.

D1-2.1.8 CAPITAL COSTS

Table D1-2-5 and Table D1-2-6 also show the building floor areas and the major capital costs for a MOX facility handling "clean" separated and solidified PuO2 (NASAP Case # (U.Pu)O2 "RO/CM" aka "RH/CM"). This information is taken directly from the relevant ORNL reports and is in 1978$. In later Tables some of these costs are adjusted by SA&I to reflect regulatory concerns and today's estimating and cost levelization practice. By placing these areas and costs on the same tables as for UOX, the comparison of the manufacturing steps and costs for the two fuel types (CAT-I versus CAT-III) is easily made. Additional columns on these two tables list the calculated factor (MOX to UOX area or cost ratio) for each major process building area. Note that the NASAP authors did not provide equipment costs for MOX at the detailed level. The total costs for the MOX facility were $204M for the process building and $208M for the equipment within, both in 1978 constant USD. The following comparison results are most noteworthy:

- The MOX process building requires three times the footprint (floor area) of the UOX process building for nearly the same annual throughput (520 kgU/yr for UOX, 480 kgHM/yr for MOX). Most of this is driven by the need to enclose most MOX process operations in gloveboxes, and the need to isolate certain steps of the MOX fabrication process by use of inside concrete walls for fire and personnel protection.
- The cost per square foot for the Safeguards and Security Category I MOX facility is five times that for the Category III UOX facility. This is driven by the need for more robust building construction, the addition of more inside wall partitions, and the very complex safety grade HVAC system.
- The process equipment cost for MOX is over eight times that for UOX. This is mainly a result of the fact that much of the equipment for the front half of the overall MOX fabrication process must be enclosed in purchased gloveboxes and inter-connecting solids-handling systems. The installation and testing costs for such gloveboxes and glovebox-qualified equipment is also high because of the glovebox radionuclide containment and spontaneous neutron & gamma shielding requirements.

- The direct capital cost of the process building, including all installed equipment, for MOX is close to nine times that for UOX. This also includes operational support areas such as storage, the change rooms, maintenance areas, and quality assurance laboratories.

There are other direct capital base costs that must be added to the process building and equipment costs, including land, site preparation, an additional building, and licensing & environmental costs including permitting. For the UOX facility model prepared by the NASAP authors a 30% engineering plus contingency cost was added to all civil structure-related costs to obtain a total overnight cost. For other fuel types, including MOX, no such allowance was added. The author of this report decided to show the capital costs for both cases (UOX and MOX) with and without the allowance, for comparability purposes, in Table D1-2-7. For both cases, the overnight cost of the MOX facility is over seven times that of the UOX facility.

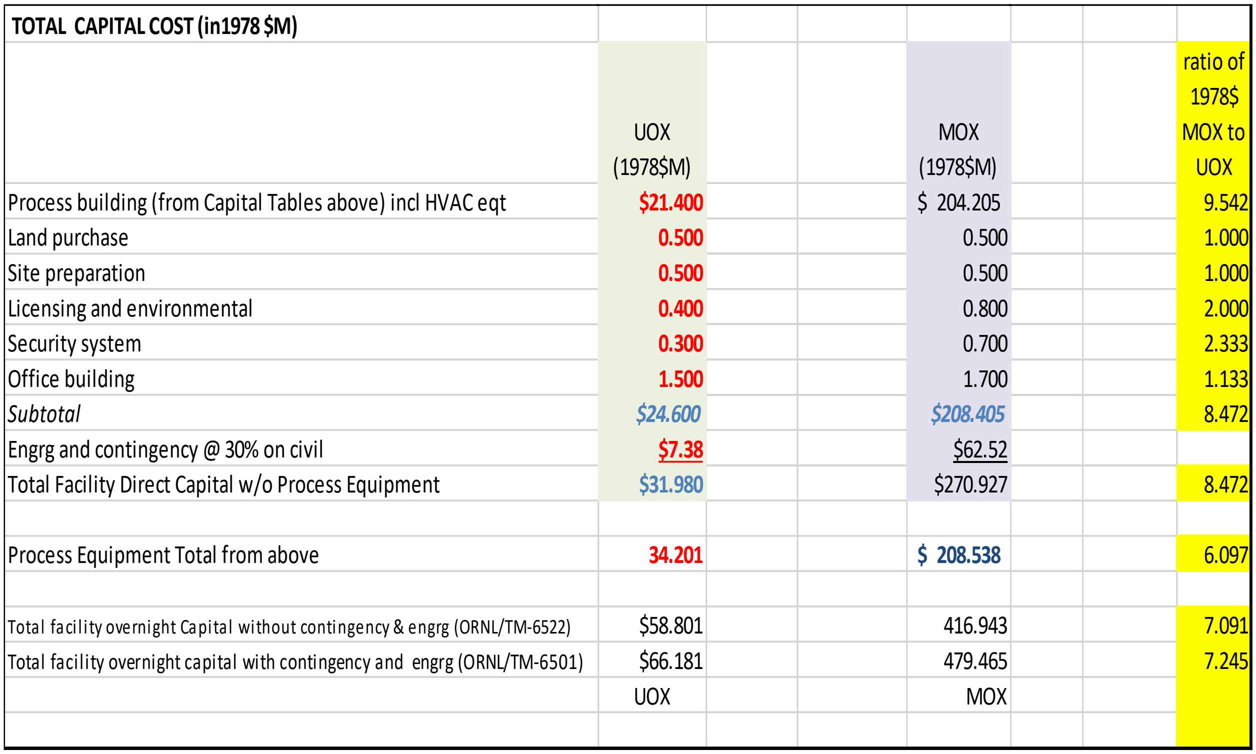
Table D1-2-5. Process Building Footprint and $/ft2 Transition from UOX to “clean” MOX per ORNL Reports (ORNL 1979. ORNLa 1979, ORNLb 1979, and ORNLc 1979) Prepared for NASAP: Fabrication Facility Floor Areas and Costs by Process Step: (Numerals in red and blue text are taken directly from the NASAP reports.)

DIRECT & INDIRECT CAPITAL COSTS from ORNL/TM reports Prepared for NASAP	Process Building							
	AREA INFO			COST INFO IN 1978$				
1. BUILDING LAYOUT AND PROCESS BUILDING COST (w/o EQT)	Reference UOX Plant Area (ft2) ornl/tm-6501	Judkins, et al calculated MOX Plant area from Table A-1 (ft2) ornl/tm-6640	Calculated Effective MOX to UOX area multiplier (process & glovebox driven)	UOX Contact handling Yr1978$ cost per ft2 ($/ft2) ornl/tm-6501	**Calculated Ref UOX Building only 1978$ cost ($M)**	MOX RH/CM Yr1978$ cost per ft2 ($/ft2) ornl/tm-6640	Effective MOX to UOX cost per unit area multiplier	RH/CM MOX Building only 1978$ cost ($M)
			(calculated: col D/col B)		lump sum (colC x colF)		(calculated: colH/colF)	lump sum cost (colG x colE x colI)
UF6 to UO2 Conversion (aqueous process) now PuO2/UO2 powder receipt	**5500**	**4420**	0.80	**200**	**1.100**	**1000**	**5.000**	4.420
MOX milling, blending, and storage	**4700**	**6760**	1.44	**200**	**0.940**	**1000**	**5.000**	6.760
Subtotal conversion to pelleting ready packaged powder	10200	11180			2.040			11.180
UO2 powder preparation and pelleting	**1900**	**3250**	1.71	**200**	**0.380**	**1000**	**5.000**	3.250
UO2 pellet sintering, grinding, and inspection	**5850**	**18445**	3.15	**200**	**1.170**	**1000**	**5.000**	18.445
Subtotal pellet production ops	7750	21695			1.550			21.695
Fuel rod loading and welding	**2780**	**5645**	2.03	**200**	**0.556**	**1000**	**5.000**	5.645
Fuel rod inspection and storage	**7000**	**16900**	2.41	**200**	**1.400**	**1000**	**5.000**	16.900
Subtotal rod loading ops	9780	22545			1.956			22.545
Fuel assembly fabrication	**3000**	**13000**	4.33	**200**	**0.600**	**1000**	**5.000**	13.000
Fuel assembly weighing, cleaning, and inspection	**3400**	**9280**	2.73	**200**	**0.680**	**1000**	**5.000**	9.280
Fuel assembly packaging and shipping	**4000**	**31200**	7.80	**200**	**0.800**	**1000**	**5.000**	31.200
Subtotal fuel assy ops	10400	53480			2.080			53.480
Scrap recovery and waste processing	**2000**	**13000**	6.50	**200**	**0.400**	**1000**	**5.000**	13.000
Subtotal Main U-handling area (Tier 1)	*40130*	*121900*	3.04	200	8.026	1000	5.00	*121.9*
	uox ft2	*mox ft2*	avg area mult	*avg $/ft2 uox*	*uox $M*	*avg $/ft2 mox*	avg unit cost mult	*mox $M*
Operational support areas including fuel assembly hardware fab (Most zirc parts are purchased as finished objects, such as tubes)	**20065**	**60950**	3.04	**200**	**4.013**	**200**	**1.000**	12.190
Ancillary support areas:								
Stores (Warehouse)	**2000**	**2600**	1.30	**200**	**0.400**	**100**	**0.500**	**0.260**
Facility support	**9135**	**48760**	5.34	**200**	**1.827**	**200**	**1.000**	**9.752**
Change rooms for contaminated areas	**2005**	**2005**	1.00	**200**	**0.401**	**361**	**1.805**	**0.724**
Quality control laboratories	**7000**	**9100**	1.30	**400**	**2.800**	**3846**	**9.615**	**35.000**
Maintenance	**19665**	**60950**	3.10	**200**	**3.933**	**400**	**2.000**	**24.380**
Subtotal ancillary floor space	39805	123415	3.10		9.361			70.115
Subtotal operational support plus ancillary floor space (Tier 2)	*59870*	*184365*	3.08	223.38	13.374	446	1.998	*82.305*
	uox ft2	*mox ft2*	avg area mult	*avg $/ft2 uox*	*$M*	*avg $/ft2 mox*	avg unit cost mult	*mox $M*
Process Building Total in ft2(col C) or $ (cols F,H,J)	**100000**	**306265**	**3.06**	214	$21.400	667	3.12	$ 204.205
	uox ft2	mox ft2	avg area ratio mox to uox	*avg $/ft2 uox*	1978$M UOX	*avg $/ft2 mox* MOX	avg unit cost mult	1978$M mox

Table D1-2-6. Transition from UOX to "clean aka RO/CM" MOX per 1978 ORNL Reports Prepared for NASAP: Process Equipment and total of Building and Equipment Direct Costs. (Numerals in red and blue text are taken directly from the NASAP reports.)

DIRECT & INDIRECT CAPITAL COSTS from ORNL/TM reports Prepared for NASAP	**Equipment** COST INFO IN 1978$			Totals **Total Bldg & Eqt UOX**	**Total Bldg & Eqt MOX**
1. BUILDING LAYOUT AND PROCESS BUILDING COST (w/o EQT)	1978$ Eqt Cost UOX	1978$ Eqt Cost MOX	1978$ MOX/UOX Cost Ratio	1978$ UOX	1978$ MOX
UF6 to UO2 Conversion (aqueous process) now PuO2/UO2 powder receipt	1.434				
MOX milling, blending, and storage	0.520				
Subtotal conversion to pelleting ready packaged powder	1.954	n/a			
UO2 powder preparation and pelleting	0.320				
UO2 pellet sintering, grinding, and inspection	3.816				
Subtotal pellet production ops	4.136	n/a			
Fuel rod loading and welding	0.650				
Fuel rod inspection and storage	1.010				
Subtotal rod loading ops	1.660	n/a			
Fuel assembly fabrication	0.280				
Fuel assembly weighing, cleaning, and inspection	0.700				
Fuel assembly packaging and shipping	2.500				
Subtotal fuel assy ops	3.480	n/a			
Scrap recovery and waste processing	0.150	**n/a**			
Subtotal Main U-handling area (Tier 1)	11.380	94.924	8.341	19.406	216.824
Operational support areas including fuel assembly hardware fab	4.268	5.811	1.36	8.281	18.001
(Most zirc parts are purchased as finished objects, such as tubes)					
Ancillary support areas:					
Stores (Warehouse)	0.060	0.078	1.30	0.460	0.338
Facility support	5.690	28.097	4.94	7.517	37.849
Change rooms for contaminated areas	0.000	0.000	1.00	0.401	0.724
Quality control laboratories	1.423	4.704	3.31	4.223	39.704
Maintenance	11.380	74.924	6.58	15.313	99.304
Subtotal ancillary floor space	18.553	107.803		27.914	177.918
Subtotal operational support plus ancillary floor space (Tier 2)	22.821	113.614	4.978	26.834	195.919
Process Building Total in ft2(col C) or $ (cols F,H,J)	34.201	208.538	6.097	46.240	412.743
	UOX EQT	MOX EQT	ratio	UOX	MOX

Table D1-2-7. NASAP Comparison of Total Capital Costs for UOX and “clean” MOX Fabrication Facilities. (Numerals in red and blue text are taken directly from the NASAP reports.)



TOTAL CAPITAL COST (in1978 $M)							
	UOX (1978$M)			MOX (1978$M)			ratio of 1978$ MOX to UOX
Process building (from Capital Tables above) incl HVAC eqt	$21.400			$ 204.205			9.542
Land purchase	0.500			0.500			1.000
Site preparation	0.500			0.500			1.000
Licensing and environmental	0.400			0.800			2.000
Security system	0.300			0.700			2.333
Office building	1.500			1.700			1.133
Subtotal	*$24.600*			*$208.405*			8.472
Engrg and contingency @ 30% on civil	$7.38			$62.52			
Total Facility Direct Capital w/o Process Equipment	$31.980			$270.927			8.472
Process Equipment Total from above	34.201			$ 208.538			6.097
Total facility overnight Capital without contingency & engrg (ORNL/TM-6522)	$58.801			416.943			7.091
Total facility overnight capital with contingency and engrg (ORNL/TM-6501)	$66.181			479.465			7.245
	UOX			MOX			

D1-2-1.3 Recurring Costs Including Annual Operations and Maintenance

Personnel salaries (including overheads) and consumables (materials and utilities) comprise the major annual costs for both the UOX and MOX facilities. The NASAP authors did a detailed staffing analysis by process step for the PWR-UOX facility, and found that a staff of 1400, many of whom are shift workers, would be required to operate and supervise the process lines. All costs were in 1978$, including the “fully loaded” salaries. The major purchased material for both UOX and MOX is the nuclear-grade zirconium metal required to fabricate hardware (tubes, spacers, plates, fixtures, etc.) that comprise the non-heavy metal parts of the fuel assembly. Table D1-2-8 shows a comparison of the personnel and consumables requirements. It can be seen that approximately 70% higher personnel costs and 20% higher materials costs are incurred for MOX vis-à-vis UOX. Other costs shown in the table are annualized equipment costs (equipment assumed replaced every 20 years), preoperational costs such as start-up of the process (really a capital cost), and decontamination & decommissioning (D&D) costs annualized by collection of an escrow fund such that D&D can be prefunded. The table also includes the assumed production rate ramp-up at commencement of operations.

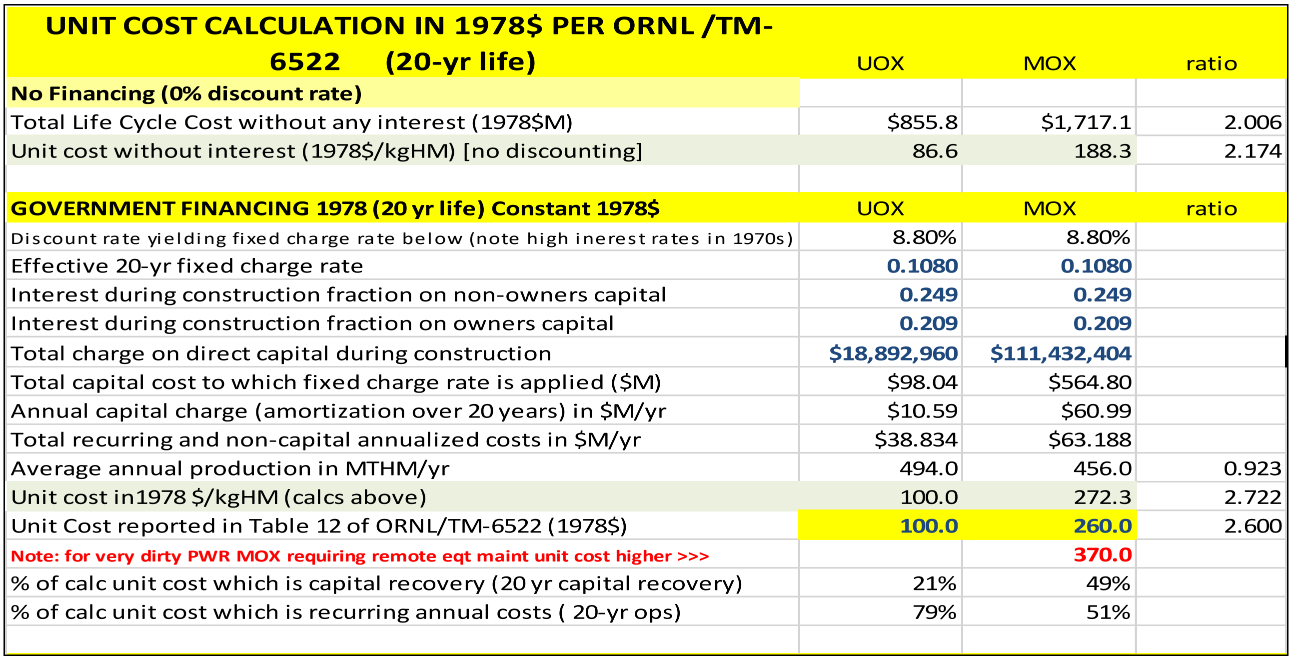
Table D1-2-8. NASAP Annualized Recurring Costs and Production for UOX and “clean” MOX for 20-year plant. (Numerals in red and blue text are taken directly from the NASAP reports.)

ANNUALIZED OPERATIONS COSTS AND PRODUCTION			
	n/a = not available: information in ORNL non-UOX reports not at this level of detail		
PERSONNEL (~1400 staff total headcount for UOX, staffing breakdown not legible in 1978 ORNL report copy)	1978$ annual totals (UOX)	1978$ annual totals (MOX)	Ratio of MOX to UOX Cost
General Management	$80,000	n/a	
Design Engineering	$720,000	n/a	
Projects	$189,000	n/a	
Finance	$309,000	n/a	
Purchasing & personnel	$455,000	n/a	
Manufacturing (all shifts)	$9,345,000	n/a	
Medical (all shifts)	$237,000	n/a	
Quality Assurance (all shifts)	$1,632,000	n/a	
Total Personnel Costs (fully-loaded salaries)	$12,967,000	$22,426,000.00	1.729
(variable portion of above total)	$10,164,000	$18,490,000	1.819
(fixed portion of above total)	$2,803,000	$3,936,000	1.404
Check total	$12,967,000	$22,426,000	1.729
Overhead & General & Administrative (G&A)	$177,000	$177,000	1.000
Utilities	$239,000	$1,363,000	5.703
Total Non-Material Recurring Costs	$13,383,000	$23,966,000	1.791
OTHER ANNUAL COSTS (Materials)	UOX	MOX	ratio
Direct and indirect materials (non-zirc)	$1,014,000	$6,330,000	6.243
Misc Supplies	$1,128,000	$1,974,000	1.750
Purchased Hardware (mostly zirc parts)	$20,899,000	$19,291,000	0.923
Total	$23,041,000	$27,595,000	1.198
			ratio
Total Recurring Costs	$36,424,000	$51,561,000	1.416
Other costs (derived by 1978 ORNL NASAP analysts)			ratio
	UOX	MOX	
Preoperations (total of 152% of one yrs annual non-materials costs: a capital owner's cost)	$20,342,160	$36,428,320	1.791
100% of eqt replaced over 20 yr ops life (ave annual cost) $/yr	$1,710,050	$10,426,900	6.097
Annual contribution to D&D fund ($/yr)	$700,000	$1,200,000	1.714
PRODUCTION	UOX	MOX	ratio
Production achieved in 1st ops yr	33.0%	33.0%	
Production achieved in 2nd ops yr	67.0%	67.0%	
Production achieved in remaining yrs	100.0%	100.0%	
Total ops years	20	20	
Total production over 20 yr ops life (MTHM)	9880	9120	0.923

D1-2.1.9 Unit Cost Calculations Using the 1978 NASAP Analysts' Assumptions

The first of the four NASAP reports, ORNL/TM-6501 (ORNL 1979), summarizes the detailed design and life cycle costs (including a calculated unit price) for a PWR UOX fabrication plant for which capital would be recovered over 20 years. No other fuel types are considered. It also includes the $/kgU (or $/kgHM) price determination results from a computerized (FORTRAN) business model which considered financial factors such as U.S. federal and local taxes, depreciation schedules, financing structure (combined equity and debt financing), and investment tax credits. The model inputs reflected the relatively high inflation rate, high interest rates, and high corporate income tax rates of the mid-to-late 1970s. The author of this Module was not yet successful in finding the source code or any detailed documentation of this "discounted cash flow business model". The model predicted that a price of ~$138/kgU (in 1978 USD) would be required to cover all UOX fabrication life cycle costs including the returns to investors. The NASAP authors did find a unit price quote from an actual fabricator to a nuclear utility, made public as part of a lawsuit settlement, and found that it was reasonably consistent with the model's prediction.

Table D1-2-9. Unit Cost Calculation for all-hands-on fabricated UOX and conventional glovebox fabricated MOX Plants having 20-year plant lives (Numerals in red and blue text are taken directly from the NASAP reports.)

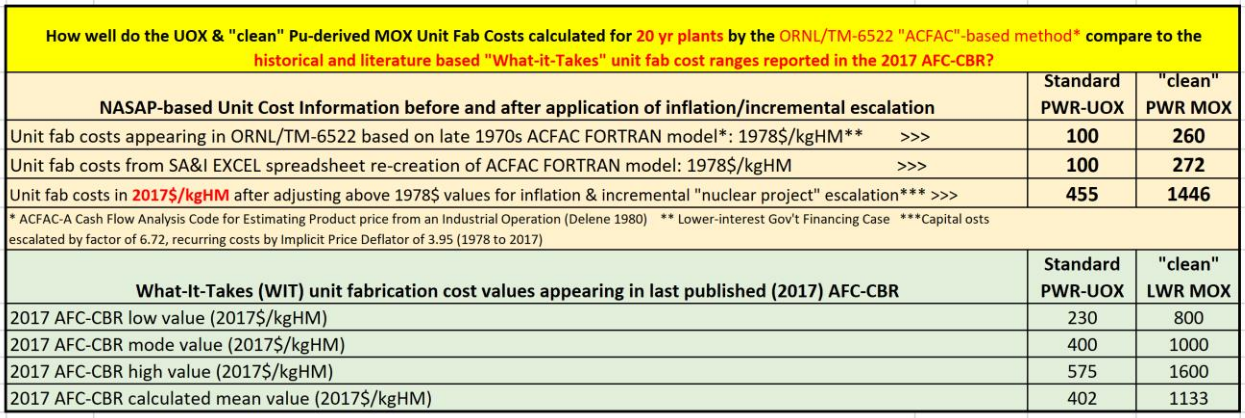


UNIT COST CALCULATION IN 1978$ PER ORNL /TM-6522 (20-yr life)	UOX	MOX	ratio
No Financing (0% discount rate)			
Total Life Cycle Cost without any interest (1978$M)	$855.8	$1,717.1	2.006
Unit cost without interest (1978$/kgHM) [no discounting]	86.6	188.3	2.174
GOVERNMENT FINANCING 1978 (20 yr life) Constant 1978$	UOX	MOX	ratio
Discount rate yielding fixed charge rate below (note high inerest rates in 1970s)	8.80%	8.80%	
Effective 20-yr fixed charge rate	**0.1080**	**0.1080**	
Interest during construction fraction on non-owners capital	**0.249**	**0.249**	
Interest during construction fraction on owners capital	**0.209**	**0.209**	
Total charge on direct capital during construction	**$18,892,960**	**$111,432,404**	
Total capital cost to which fixed charge rate is applied ($M)	$98.04	$564.80	
Annual capital charge (amortization over 20 years) in $M/yr	$10.59	$60.99	
Total recurring and non-capital annualized costs in $M/yr	$38.834	$63.188	
Average annual production in MTHM/yr	494.0	456.0	0.923
Unit cost in1978 $/kgHM (calcs above)	100.0	272.3	2.722
Unit Cost reported in Table 12 of ORNL/TM-6522 (1978$)	**100.0**	**260.0**	2.600
Note: for very dirty PWR MOX requiring remote eqt maint unit cost higher >>>		**370.0**	
% of calc unit cost which is capital recovery (20 yr capital recovery)	21%	49%	
% of calc unit cost which is recurring annual costs (20-yr ops)	79%	51%	

The three subsequent reports (ORNL 1979a, 1979b and 1979c), describe how the "reference" PWR UOX fabrication plant design and cost estimate was transitioned to design and cost estimates for several other fuel types (PHWR, HTGR, and LMFBR [SFR]) of varying nuclear material (U,Pu, and Th) compositions and combinations thereof. The use of factor analysis for transitioning from "reference PWR" to non-PWR fuels is described as well as a new, simpler NASAP levelized unit cost model called ACFAC (Delene 1980) based on simpler algorithms that can be applied to all fuel types. The newer algorithms are less "country specific" and do not include taxation or depreciation considerations; hence they are not really a "business model" for price calculation. (This module is concerned in projected comparative unit costs, rather than in “balanced market” price setting.) They do, however, consider a 20-year plant operating life with 20-year amortization of capital via a fixed charge rate. Even for the lowest risk case they considered, a government-financed plant, the real (inflation-free) discount rate assumed for the analysis was high by today’s (2018) standards at around 8.8%. Table D1-2-9 above shows the parameters for the calculation (in 1978 USD) of both the 20-year plant UOX and MOX unit costs, and how these EXCEL spreadsheet calculations compare with values calculated by the NASAP analysts with the FORTRAN models mentioned above. This gave the authors of this report confidence in the computational aspects of the NASAP methodology and in the assumption that it could be expanded to fuel types other than PWR UOX and PWR MOX.

When comparing the UOX and MOX unit costs calculated by the NASAP (ORNL/TM-6522, ORNL 1979a) method (and escalated to 2017 USD as discussed in a later paragraph) to those in the Sept 2107 Advanced Fuel Cycle Basis Report for the corresponding fuel fabrication modules (respectively D1-1 and D1-2), as shown in Table D1-2-10, it is observed that the escalated NASAP values fall well within the 2017 AFC-CBR UOX and MOX fabrication unit cost ranges, but on the high side of the mode (aka most-likely) of the UOX and MOX unit cost ranges for fresh LWR fuel fabrication appearing in Modules D1-1 and D1-2 of the 2017 AFC-CBR.

Table D1-2-10. Comparison of NASAP UOX and “clean” MOX Unit Fabrication Costs to those in 2017 AFC-CBR



How well do the UOX & "clean" Pu-derived MOX Unit Fab Costs calculated for 20 yr plants by the ORNL/TM-6522 "ACFAC"-based method* compare to the historical and literature based "What-it-Takes" unit fab cost ranges reported in the 2017 AFC-CBR?

NASAP-based Unit Cost Information before and after application of inflation/incremental escalation	Standard PWR-UOX	"clean" PWR MOX
Unit fab costs appearing in ORNL/TM-6522 based on late 1970s ACFAC FORTRAN model*: 1978$/kgHM** >>>	**100**	**260**
Unit fab costs from SA&I EXCEL spreadsheet re-creation of ACFAC FORTRAN model: 1978$/kgHM >>>	**100**	**272**
Unit fab costs in **2017$/kgHM** after adjusting above 1978$ values for inflation & incremental "nuclear project" escalation*** >>>	**455**	**1446**
* ACFAC-A Cash Flow Analysis Code for Estimating Product price from an Industrial Operation (Delene 1980) ** Lower-interest Gov't Financing Case ***Capital osts escalated by factor of 6.72, recurring costs by Implicit Price Deflator of 3.95 (1978 to 2017)		
What-It-Takes (WIT) unit fabrication cost values appearing in last published (2017) AFC-CBR	**Standard PWR-UOX**	**"clean" LWR MOX**
2017 AFC-CBR low value (2017$/kgHM)	230	800
2017 AFC-CBR mode value (2017$/kgHM)	400	1000
2017 AFC-CBR high value (2017$/kgHM)	575	1600
2017 AFC-CBR calculated mean value (2017$/kgHM)	402	1133

D1-2.1.10 2017 Constant-Dollar UOX and MOX Fabrication Unit Cost Determination Using 1978 Base Costs from NASAP Reports and Current FCRD-SA&I Economic Modeling Criteria

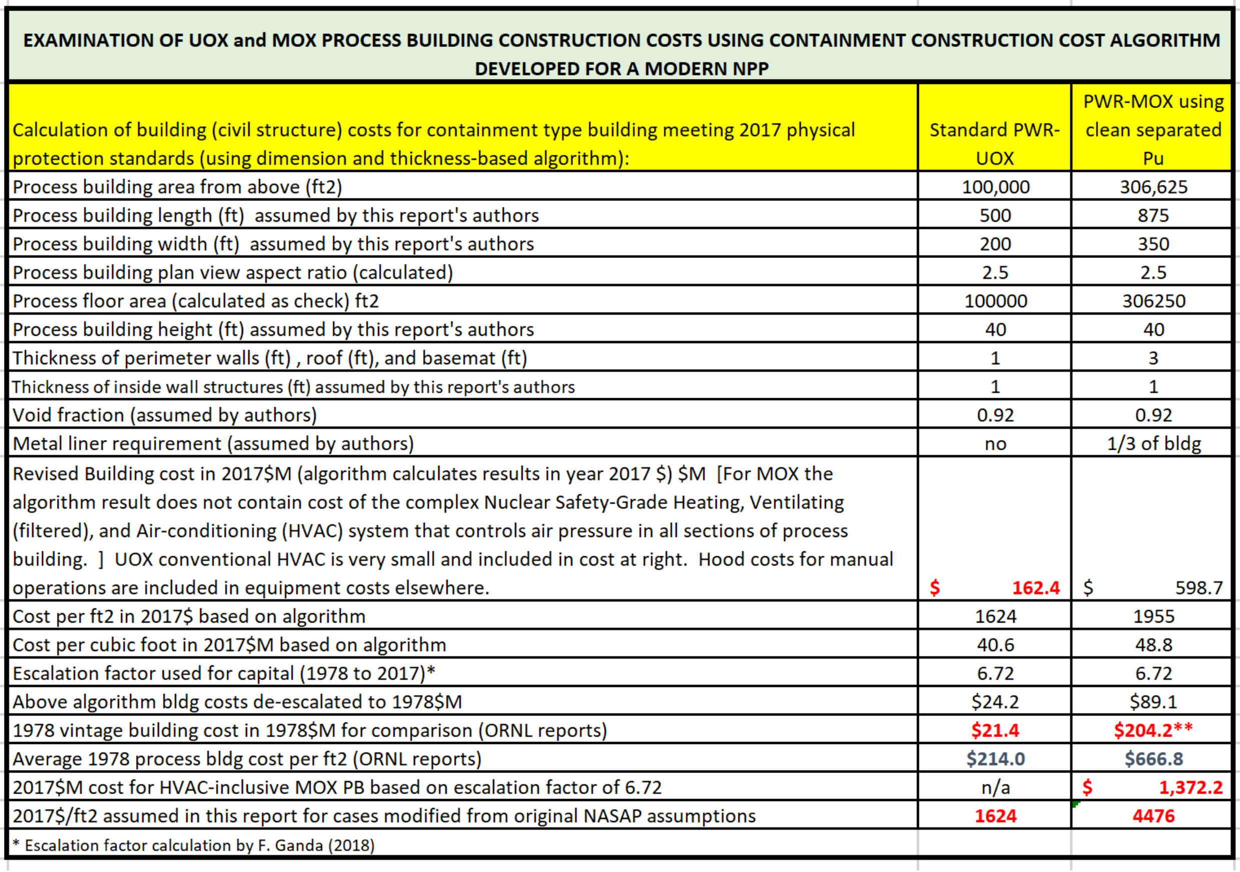
A more realistic unit cost for today’s economy can be obtained by taking the base capital, recurring cost, and annual production information from the NASAP reports and utilizing selected macroeconomic parameters more in tune with the way comparative techno-economic assessments are done today. The approach taken here is consistent with, among others, the one described in the Generation IV Reactor Cost Estimating Guidelines (EMWG 2007). The following changes, as compared to the NASAP assumptions described in the previous paragraph, are made in the modeling methodology and in certain economic inputs thereto:

- The plant operational and capital recovery lifetime is extended from 20 to 50 years. A well-built and well-maintained fuel fabrication facility should last at least 50 years with periodic equipment replacements. The fact the USNRC now licenses NPPs for 60 years adds to the confidence that such longevity is possible for fuel cycle facilities. As an example, France has also successfully operated their LaHague reprocessing facility and their MELOX MOX fabrication facilities for over 40 and 26 years respectively. The same capital cost, even with interest, can now be spread over more years of production, thus resulting in a reduction in the levelized unit cost of product.

- Substantially lower interest rates, in the form of real discount rates, can be assumed for the calculation of interest during construction (IDC), capital recovery (amortization), and for the interest rate collected annually by the sinking fund to cover decontamination and decommissioning (D&D) at the facility end-of-life (EOL). 3% is assumed for IDC and capital recovery, and 1.5% for the sinking fund.
- In the NASAP reports no algorithm was given for the calculation of Interest During Construction. For the calculation below, the IDC is based on an S-curve cumulative expenditure pattern for the project capital spread over some number of years specified by the user. For the UOX plant 5 years for construction is assumed. For the more complex MOX plant, 7 years is assumed. A continuous interest rate algorithm is used instead of a discrete model based on quarterly payments. This is the only deviation from G4-ECONS methodology described in (G4-ECONS 2007) and was done for simplification. The IDC values calculated by both methods differ by less than 2%.
- A capital recovery factor (CRF) based on 50-years of annual payments at 3% annual interest (real discount rate) is used to amortize the sum of the overnight cost plus the IDC. The CRF formula is given in (Ref 5: EMWG 2007) and in Module D1-1 (Ceramic UOX). The annual capital recovery payments are the same for all 50-years, hence the term “levelized” cost.
- The lump sum cost required for D&D at facility EOL is assumed to be 10% of the direct capital cost (without contingency, indirect costs, or IDC) of the facility. Another simple algorithm, also appearing in Module D1-1, is used to calculate the sinking fund factor (SFF). It is also given in the Gen IV Cost Estimating Guidelines document. The annual amount needed (for all 50 years) for the sinking or “escrow” fund is the SFF times the lump sum cost required for D&D. A lower discount rate (1.5%) is used, since it is difficult to obtain a long- term sinking fund investment at a higher interest rate. The NASAP analysts also considered annual D&D costs; however, no algorithm for their calculation was given.
- Production from the hypothetical facility, in terms of kilograms of heavy metal per year, is the same for all 50-years. No production ramp-up or ramp-down is assumed. This assumption simplifies the calculation of the levelized unit cost. Preoperational costs, calculated by the NASAP analysts at ~150% of one year’s recurring costs, account for startup costs and are part of the overnight capital cost subject to imposition of IDC and capital recovery.
- Recurring costs were handled similarly as in the NASAP reports, except that we assume them for 50 years instead of 20 years. Replacement of plant equipment is annualized for simplification purposes. Realistically these replacement costs would vary widely year-by-year. Again, the “levelization” methodology requires this annualization assumption. It is assumed that equipment is replaced every ten years, hence the annual amount is the direct equipment capital cost divided by 10 and the resulting quotient spent for all 50 years.
- The authors of this module decided to check the appropriateness of the process building civil structure capital cost (without the equipment it contains.) This was done in response to the more stringent NRC and DOE imposed criteria for protection from external manmade threats, extreme natural phenomena, and reduced source-term from radiation releases or fire. Some of these were imposed as a result of the terrorist attacks of September 11, 2001 in the USA. One of this module’s authors utilized a cost scaling algorithm developed for concrete and steel nuclear reactor containments (Ganda 2018) to assess the values assumed by the NASAP analysts. If 1-foot thick reinforced concrete walls are assumed for the UOX plant walls and roof, a 2017$ cost of $162M would result for the building cost. De-escalating this to 1978$ results in a $24M cost, which is slightly higher than the 21$M cost

originally estimated by the NASAP analysts. This fact convinced the authors of this module that the NASAP analysts assumed a reasonably conservative building structure design, and likely adopted this design philosophy for the more complex buildings needed for MOX and other fuels with more radiotoxic fuel components. Applying the same algorithm to a larger, more robust MOX building with 3-ft thick walls and roof, resulted in a cost of nearly $600M in 2017$, which would be $89M in 1978$M. The actual value calculated by the NASAP analysts for the MOX building was $204M in then-year (1978$), which would translate to well over $1.5 billion today. It has been determined that the higher value used by the NASAP analysts includes the complex HVAC and air pressure control system needed for MOX fabrication but not for UOX. For this reason, the higher value used in the 1978 NASAP analysis is used for this calculation. Table D1-2-11 shows the parameters for the building cost verification calculation and the results.

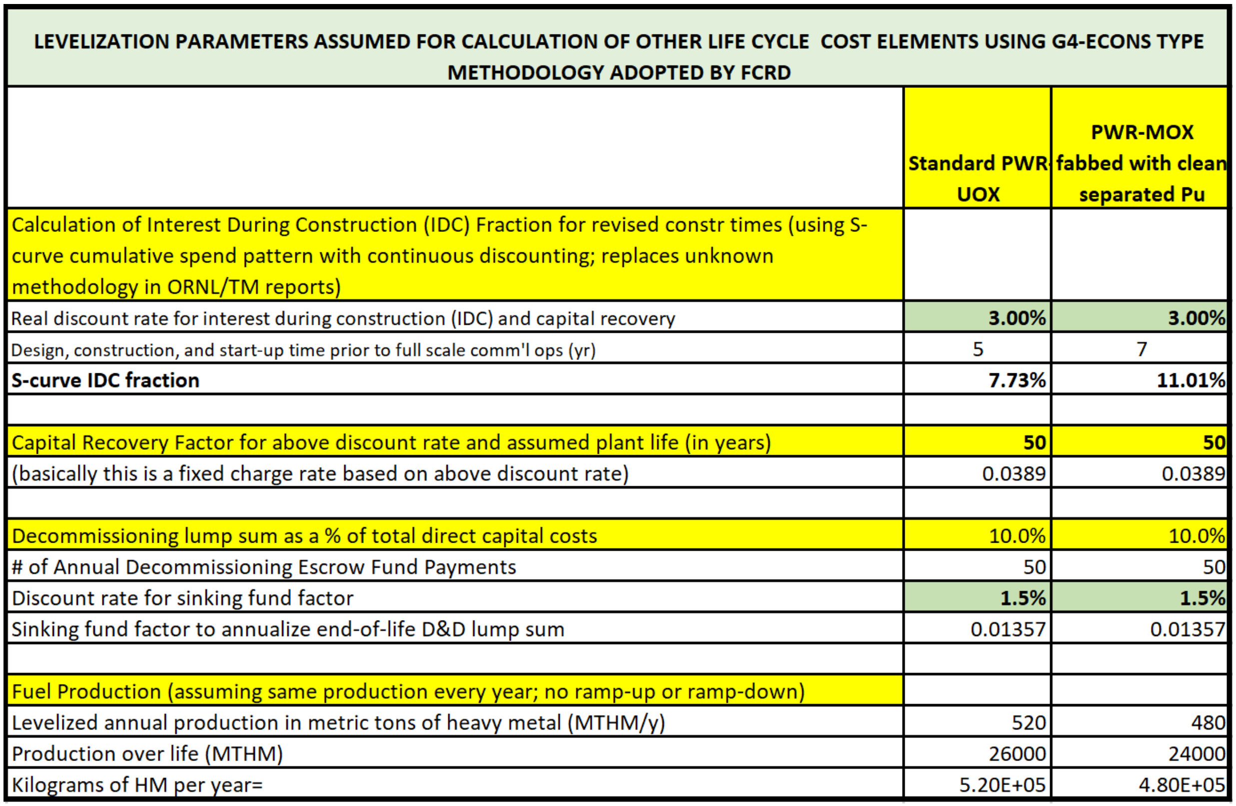
Table D1-2-11. Process Building Cost Verification for Hypothetical UOX and “clean”MOX Fabrication Facilities



EXAMINATION OF UOX and MOX PROCESS BUILDING CONSTRUCTION COSTS USING CONTAINMENT CONSTRUCTION COST ALGORITHM DEVELOPED FOR A MODERN NPP		
Calculation of building (civil structure) costs for containment type building meeting 2017 physical protection standards (using dimension and thickness-based algorithm):	Standard PWR-UOX	PWR-MOX using clean separated Pu
Process building area from above (ft2)	100,000	306,625
Process building length (ft) assumed by this report's authors	500	875
Process building width (ft) assumed by this report's authors	200	350
Process building plan view aspect ratio (calculated)	2.5	2.5
Process floor area (calculated as check) ft2	100000	306250
Process building height (ft) assumed by this report's authors	40	40
Thickness of perimeter walls (ft) , roof (ft), and basemat (ft)	1	3
Thickness of inside wall structures (ft) assumed by this report's authors	1	1
Void fraction (assumed by authors)	0.92	0.92
Metal liner requirement (assumed by authors)	no	1/3 of bldg
Revised Building cost in 2017$M (algorithm calculates results in year 2017 $) $M [For MOX the algorithm result does not contain cost of the complex Nuclear Safety-Grade Heating, Ventilating (filtered), and Air-conditioning (HVAC) system that controls air pressure in all sections of process building.] UOX conventional HVAC is very small and included in cost at right. Hood costs for manual operations are included in equipment costs elsewhere.	$ 162.4	$ 598.7
Cost per ft2 in 2017$ based on algorithm	1624	1955
Cost per cubic foot in 2017$M based on algorithm	40.6	48.8
Escalation factor used for capital (1978 to 2017)*	6.72	6.72
Above algorithm bldg costs de-escalated to 1978$M	$24.2	$89.1
1978 vintage building cost in 1978$M for comparison (ORNL reports)	$21.4	$204.2**
Average 1978 process bldg cost per ft2 (ORNL reports)	$214.0	$666.8
2017$M cost for HVAC-inclusive MOX PB based on escalation factor of 6.72	n/a	$ 1,372.2
2017$/ft2 assumed in this report for cases modified from original NASAP assumptions	1624	4476
* Escalation factor calculation by F. Ganda (2018)		

Table D1-2-12 shows the results of the application of G4-ECONS type algorithms, including those for levelization, for the calculation of the capital recovery factor, sinking fund factor, and interest during construction fraction. These factors allow the base capital and recurring life cycle costs from the NASAP studies to be converted into annual expenditures per the “levelization” requirement. It also shows the levelized production assumed for both the UOX and MOX facilities. Dividing the levelized annual costs by the levelized production, allows the calculation of a total levelized unit cost which can be broken down into relative $/kgHM contributions from capital recovery, recurring costs, and D&D fund costs.

Table D1-2-12. Calculation of Levelization and Interest-related Parameters for Unit Cost Determination using G4-ECONS Methodology



LEVELIZATION PARAMETERS ASSUMED FOR CALCULATION OF OTHER LIFE CYCLE COST ELEMENTS USING G4-ECONS TYPE METHODOLOGY ADOPTED BY FCRD

	Standard PWR UOX	**PWR-MOX fabbed with clean separated Pu**
Calculation of Interest During Construction (IDC) Fraction for revised constr times (using S-curve cumulative spend pattern with continuous discounting; replaces unknown methodology in ORNL/TM reports)		
Real discount rate for interest during construction (IDC) and capital recovery	**3.00%**	**3.00%**
Design, construction, and start-up time prior to full scale comm'l ops (yr)	5	7
S-curve IDC fraction	**7.73%**	**11.01%**
Capital Recovery Factor for above discount rate and assumed plant life (in years)	**50**	**50**
(basically this is a fixed charge rate based on above discount rate)	0.0389	0.0389
Decommissioning lump sum as a % of total direct capital costs	10.0%	10.0%
# of Annual Decommissioning Escrow Fund Payments	50	50
Discount rate for sinking fund factor	**1.5%**	**1.5%**
Sinking fund factor to annualize end-of-life D&D lump sum	0.01357	0.01357
Fuel Production (assuming same production every year; no ramp-up or ramp-down)		
Levelized annual production in metric tons of heavy metal (MTHM/y)	520	480
Production over life (MTHM)	26000	24000
Kilograms of HM per year=	5.20E+05	4.80E+05

D1-2.1.11 CALCULATION OF UNIT COSTS IN 1978 USD AND ESCALATION TO 2017 USD

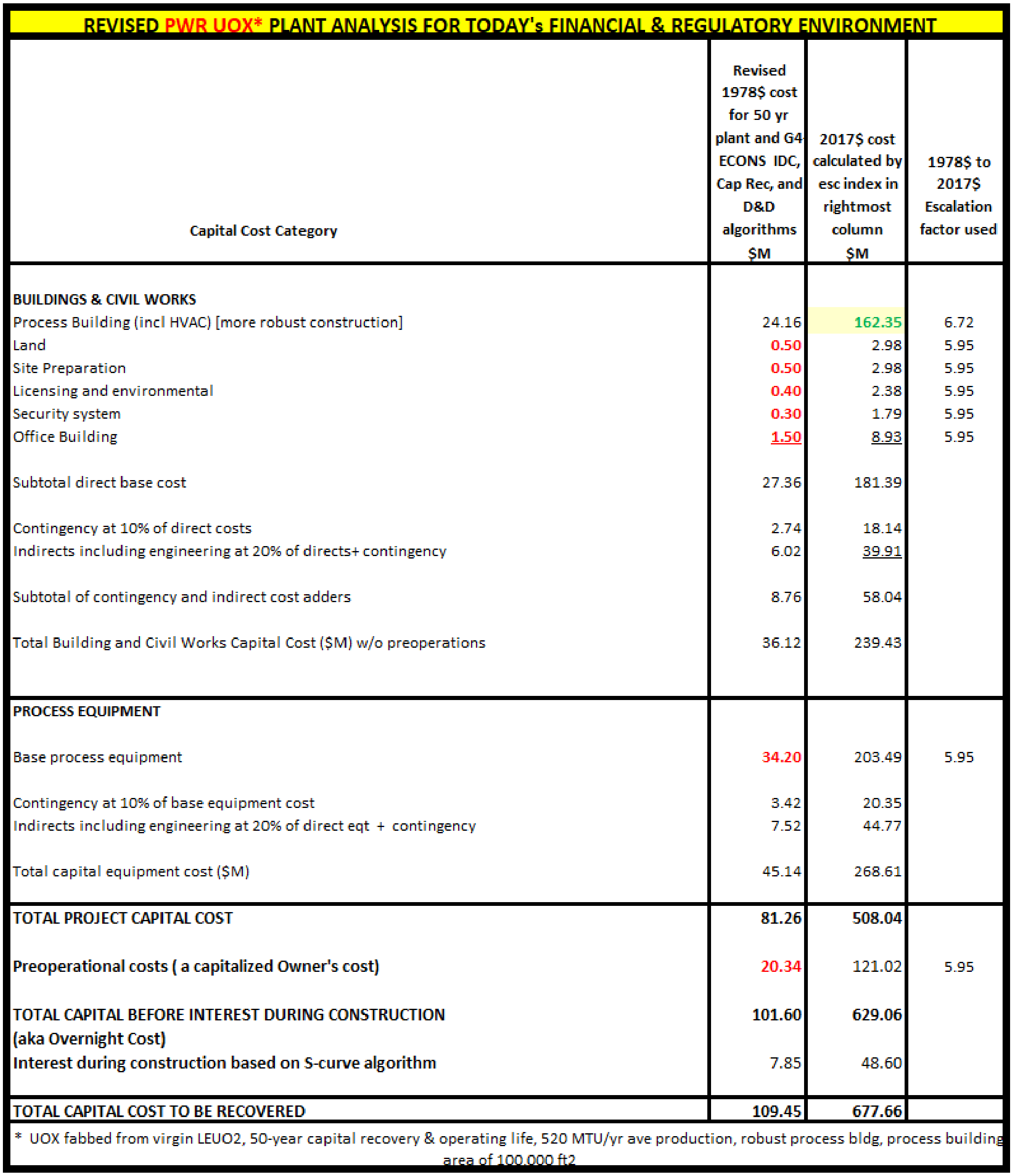
A major issue that had to be addressed by the authors of this module was that of escalating the results of the UOX to MOX transitional analysis from 1978 USD to 2017 USD. This adjustment is necessary in order to use the results of the above analysis as part of the cost basis supporting the unit cost ranges and distributions appearing in the 2017 AFC-CBR, where all summary results are given in 2017 USD. Not only does nearly 40 years of general inflation (from 1978 to 2017) need to be considered, but also the incremental escalation above inflation endemic to the nuclear industry capital costs for many years, especially from 1965 through the mid-1990s. The annual incremental "nuclear" escalation rate was around 3% during the years most US LWRs were constructed. For the 18 years from 1978 to 1996 the accumulation of this escalation rate would result in an additional index of 1.79 [1.033 to the 18th power] . Multiplying this 1.7 incremental factor times the CPI-based index of 3.75 (1978 to 2017) gives an overall "nuclear project" index of 6.72 which can be applied to those structures and items requiring "nuclear certified" (NQA-1) construction, manufacturing, and installation. Table D1-2-13 shows where each of the three factors of 3.95 (CPI-only), 5.95 (nuclear market basket index from 2017 AFC-CBR), and 6.72 (inclusive of NQA-1 nuclear escalation) are applied for the various life cycle categories of the UOX and MOX fabrication facilities.

Table D1-2-13. Escalation: Multiplication factors used to convert 1978$ to 2017$ for various life cycle categories for the SA&I modified "reference" LWR fuel fabrication facility and the "subject" MOX facility.

Composite Inflation-Escalation Factor (2017 cost/1978 cost) A multiplier for use on the 40-year, robust fab plants using SA&I regulatory and economic assumptions	Indices utilized for multiplication factor calculation and rationale for use	Life cycle cost categories for which it is applied
6.72	Ratio of algorithm-developed capital cost (in 2017$) for a reinforced concrete NQA-1 "robust" process building (incl HVAC) to the 1978$ robust process building. The assumptions are discussed in the text calling out this table. The multiplier for the non-robust building cost in ORNL/TM-6501(ORNL 1979) would be 7.58	Main Process Building Capital cost including HVAC, environmental support, & security systems capital costs
5.95	1978 to 2017 Nuclear.Market Basket: Table 8.3 of 2017 AFC-CBR (Dixon, et al 2017). Table is developed from multiple nuclear project-related indices such as Handy-Whitman (WRA 2020), DOE Nuclear Construction, PCCI, and IPD. Includes nuclear escalation, but not as much as for NQA-1 items in category above	Capital cost of auxiliary buildings, process equipment, preoperational costs, and replacement equipment
3.75	Consumer Price Index (CPI) from 1978 to 2017. Since this factor is applied to mostly personnel related, recurring costs, it was felt that the consumer item "market basket" essentially covered by worker salaries would be more appropriate than the more generic implicit price deflator (IPD). Recurring costs are also much less subject to nuclear-related cost-risks than capital costs.	Recurring costs such as fully-loaded labor and general/administrative (G&A) costs, purchased material costs, utility costs

Table D1-2-14 and Table D1-2-15 show the new life cycle cost breakdown for a UOX fuel fabrication plant operating for 50-years and a capital recovery period of 50 years. Table D1-2-14 is the capital cost breakdown and Table D1-2-15 covers the recurring and D&D costs. (MOX is considered in later Tables)

Table D1-2-14. UOX fabrication facility Capital Life Cycle Costs in Both 1978$ and 2017$, including selective application of CPI-based and "nuclear" escalation

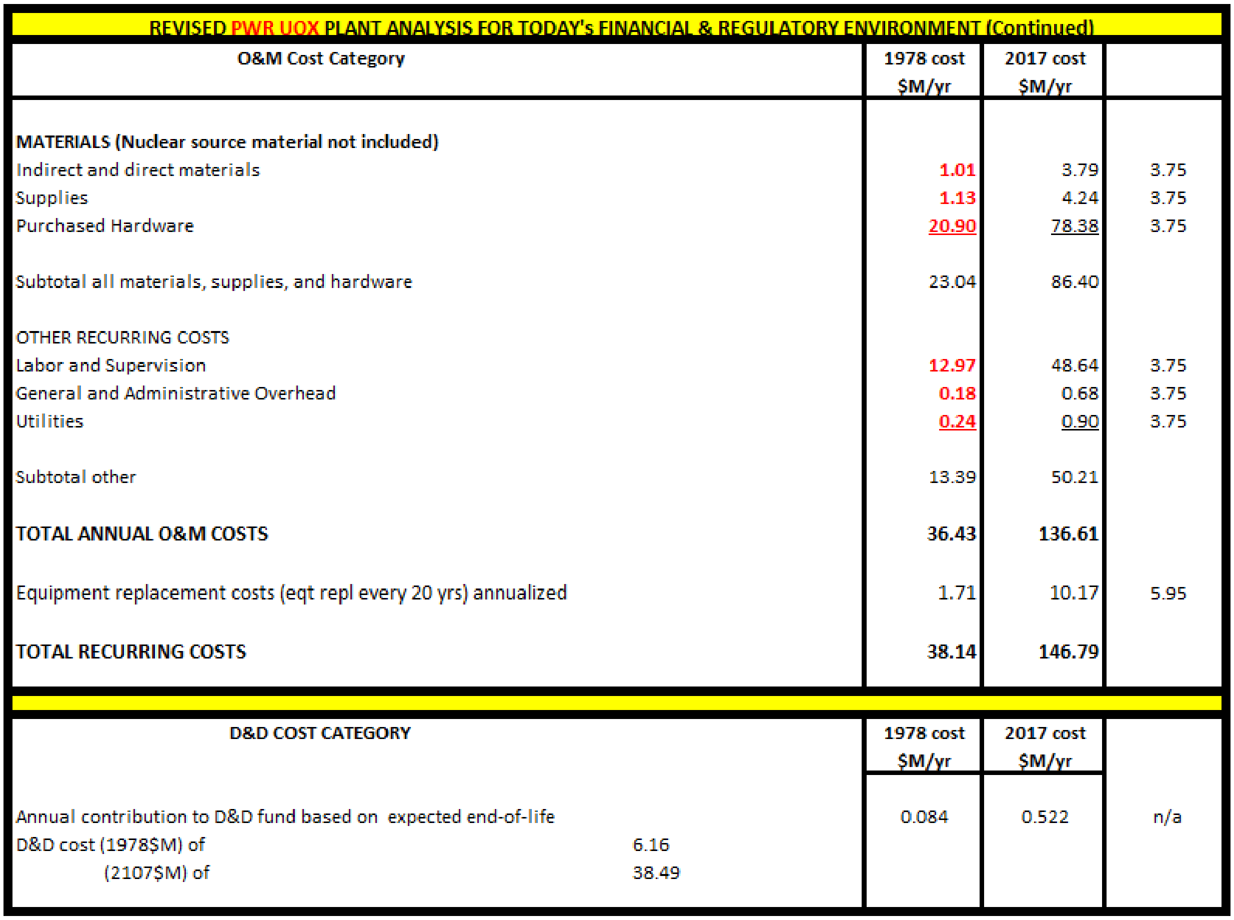


REVISED PWR UOX* PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT

Capital Cost Category	Revised 1978$ cost for 50 yr plant and G4 ECONS IDC, Cap Rec, and D&D algorithms $M	2017$ cost calculated by esc index in rightmost column $M	1978$ to 2017$ Escalation factor used
BUILDINGS & CIVIL WORKS			
Process Building (incl HVAC) [more robust construction]	24.16	162.35	6.72
Land	0.50	2.98	5.95
Site Preparation	0.50	2.98	5.95
Licensing and environmental	0.40	2.38	5.95
Security system	0.30	1.79	5.95
Office Building	1.50	8.93	5.95
Subtotal direct base cost	27.36	181.39	
Contingency at 10% of direct costs	2.74	18.14	
Indirects including engineering at 20% of directs+ contingency	6.02	39.91	
Subtotal of contingency and indirect cost adders	8.76	58.04	
Total Building and Civil Works Capital Cost ($M) w/o preoperations	36.12	239.43	
PROCESS EQUIPMENT			
Base process equipment	34.20	203.49	5.95
Contingency at 10% of base equipment cost	3.42	20.35	
Indirects including engineering at 20% of direct eqt + contingency	7.52	44.77	
Total capital equipment cost ($M)	45.14	268.61	
TOTAL PROJECT CAPITAL COST	**81.26**	**508.04**	
Preoperational costs (a capitalized Owner's cost)	20.34	121.02	5.95
TOTAL CAPITAL BEFORE INTEREST DURING CONSTRUCTION (aka Overnight Cost)	**101.60**	**629.06**	
Interest during construction based on S-curve algorithm	7.85	48.60	
TOTAL CAPITAL COST TO BE RECOVERED	**109.45**	**677.66**	

* UOX fabbed from virgin LEUO2, 50-year capital recovery & operating life, 520 MTU/yr ave production, robust process bldg, process building area of 100,000 ft2

Table D1-2-15. UOX facility recurring and D&D costs for 50-year operations and D&D sinking fund accumulation

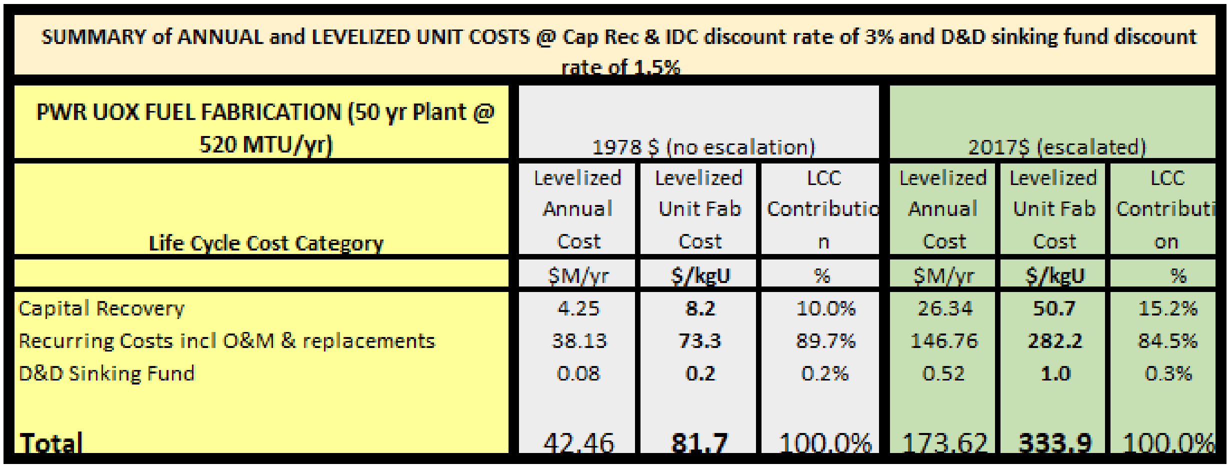


REVISED PWR UOX PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT (Continued)			
O&M Cost Category	**1978 cost $M/yr**	**2017 cost $M/yr**	
MATERIALS (Nuclear source material not included)			
Indirect and direct materials	1.01	3.79	3.75
Supplies	1.13	4.24	3.75
Purchased Hardware	20.90	78.38	3.75
Subtotal all materials, supplies, and hardware	23.04	86.40	
OTHER RECURRING COSTS			
Labor and Supervision	12.97	48.64	3.75
General and Administrative Overhead	0.18	0.68	3.75
Utilities	0.24	0.90	3.75
Subtotal other	13.39	50.21	
TOTAL ANNUAL O&M COSTS	**36.43**	**136.61**	
Equipment replacement costs (eqt repl every 20 yrs) annualized	1.71	10.17	5.95
TOTAL RECURRING COSTS	**38.14**	**146.79**	
D&D COST CATEGORY	**1978 cost $M/yr**	**2017 cost $M/yr**	
Annual contribution to D&D fund based on expected end-of-life D&D cost (1978$M) of 6.16 (2107$M) of 38.49	0.084	0.522	n/a

Table D1-2-16 shows the breakdown of the 50-year UOX Fabrication plant levelized unit production cost in both 1978 and 2017 dollars per kgU (or $/kgHM). Note that this is a service or “toll” cost and does not include the cost of the low-enriched UF6 needed as feed. It is noted that going from a 20 year to a 50 year production and capital recovery life has reduced the unit cost. It can also be noted that UOX production costs are dominated by the annual recurring cost and a need for a staff of over 1000 full-time equivalents (FTEs).

Table D1-2-17 shows where each of the three factors of 3.95 (CPI-only), 5.95 (nuclear market basket) and 6.72 (inclusive of higher nuclear escalation for NQA-1) are applied for the life cycle costs of the more conventional MOX fabrication facility using “clean” PuO2 which has quickly been received from an aqueous reprocessing facility and has not had time for hazardous-level gamma-emitting decay products to build in.

Table D1-2-16. Breakdown of Unit Production Cost for a hypothetical NOAK 520MTU/yr UOX fabrication Plant



SUMMARY of ANNUAL and LEVELIZED UNIT COSTS @ Cap Rec & IDC discount rate of 3% and D&D sinking fund discount rate of 1.5%

PWR UOX FUEL FABRICATION (50 yr Plant @ 520 MTU/yr)	1978 $ (no escalation)			2017$ (escalated)		
Life Cycle Cost Category	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution
	$M/yr	**$/kgU**	%	$M/yr	**$/kgU**	%
Capital Recovery	4.25	**8.2**	10.0%	26.34	**50.7**	15.2%
Recurring Costs incl O&M & replacements	38.13	**73.3**	89.7%	146.76	**282.2**	84.5%
D&D Sinking Fund	0.08	**0.2**	0.2%	0.52	**1.0**	0.3%
Total	42.46	**81.7**	100.0%	173.62	**333.9**	100.0%

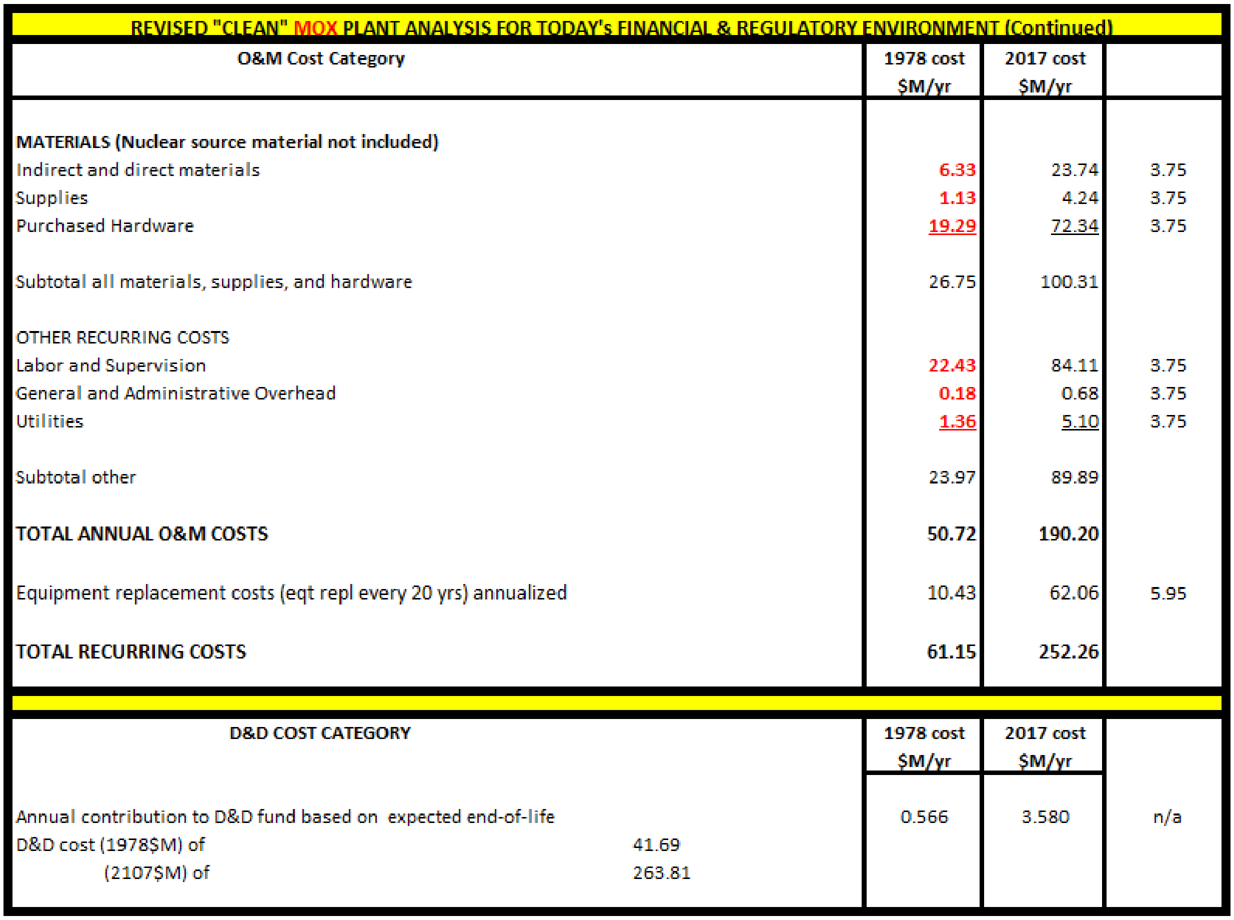
Table D1-2-17. “Clean” MOX Fabrication facility Life Cycle Capital Costs in Both 1978$ and 2017$ Including selective application of CPI-based and “nuclear” escalation factors.

REVISED PWR "CLEAN" MOX* PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT

Capital Cost Category	Revised 1978$ cost for 50 yr plant and G4 ECONS IDC, Cap Rec, and D&D algorithms $M	2017$ cost calculated by esc index in rightmost column $M	1978$ to 2017$ Escalation factor used
BUILDINGS & CIVIL WORKS			
Process Building (incl HVAC) [more robust construction]	204.21	1372.26	6.72
Land	0.50	2.98	5.95
Site Preparation	0.50	2.98	5.95
Licensing and environmental	0.80	4.76	5.95
Security system	0.70	4.17	5.95
Office Building	1.70	10.12	5.95
Subtotal direct base cost	208.41	1397.25	
Contingency at 10% of direct costs	20.84	139.73	
Indirects including engineering at 20% of directs+ contingency	45.85	307.40	
Subtotal of contingency and indirect cost adders	66.69	447.12	
Total Building and Civil Works Capital Cost ($M) w/o preoperations	275.10	1844.37	
PROCESS EQUIPMENT			
Base process equipment	208.54	1240.80	5.95
Contingency at 10% of base equipment cost	20.85	124.08	
Indirects including engineering at 20% of direct eqt + contingency	45.88	272.98	
Total capital equipment cost ($M)	275.27	1637.86	
TOTAL PROJECT CAPITAL COST	**550.37**	**3482.23**	
Preoperational costs (a capitalized Owner's cost)	36.43	216.76	5.95
TOTAL CAPITAL BEFORE INTEREST DURING CONSTRUCTION (aka Overnight Cost)	**586.80**	**3698.98**	
Interest during construction based on S-curve algorithm	64.62	407.34	
TOTAL CAPITAL COST TO BE RECOVERED	**651.42**	**4106.32**	

* MOX fabbed quickly from "clean" PuO2 product from reprocessing plant, 50-year capital recovery & operating life, 480 MTU/yr ave production very robust CAT-I process bldg, process building are of 306,265 ft2

Table D1-2-18. “Clean” MOX facility recurring and D&D costs for 50 years of operations and 50-yrs for D&D sinking fund accumulation



REVISED "CLEAN" MOX PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT (Continued)

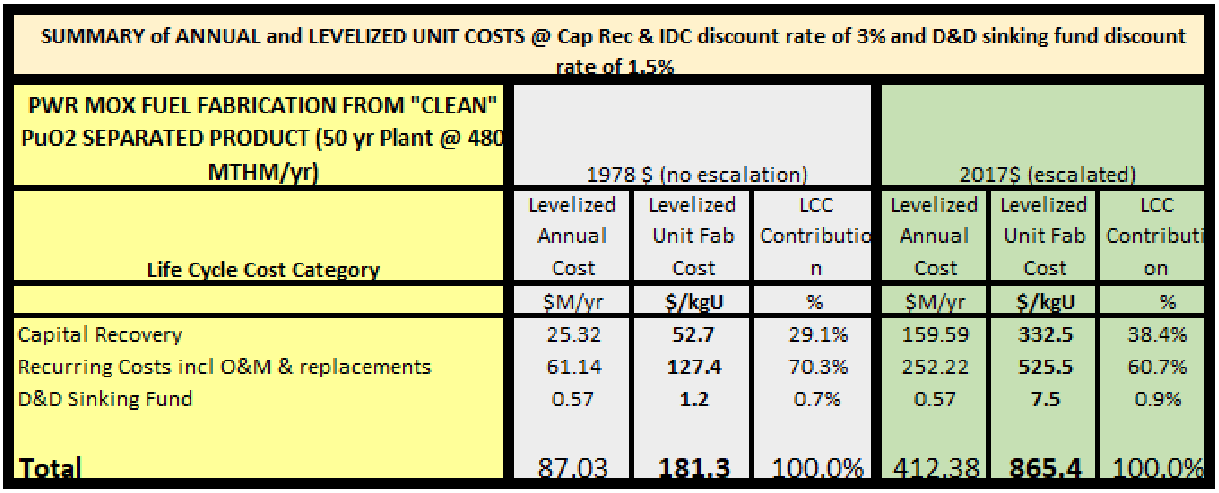
O&M Cost Category	1978 cost $M/yr	2017 cost $M/yr	
MATERIALS (Nuclear source material not included)			
Indirect and direct materials	6.33	23.74	3.75
Supplies	1.13	4.24	3.75
Purchased Hardware	19.29	72.34	3.75
Subtotal all materials, supplies, and hardware	26.75	100.31	
OTHER RECURRING COSTS			
Labor and Supervision	22.43	84.11	3.75
General and Administrative Overhead	0.18	0.68	3.75
Utilities	1.36	5.10	3.75
Subtotal other	23.97	89.89	
TOTAL ANNUAL O&M COSTS	**50.72**	**190.20**	
Equipment replacement costs (eqt repl every 20 yrs) annualized	10.43	62.06	5.95
TOTAL RECURRING COSTS	**61.15**	**252.26**	

D&D COST CATEGORY		1978 cost $M/yr	2017 cost $M/yr	
Annual contribution to D&D fund based on expected end-of-life		0.566	3.580	n/a
D&D cost (1978$M) of	41.69			
(2107$M) of	263.81			

It is noted that for MOX the higher escalation factor of 6.72 was applied to recurring personnel costs. This is a result of the fact that today’s regulations require a much higher security, safety, and health physics staff for a plant containing radiotoxic and strategic nuclear material. A MOX plant this large (480 MTHM/yr) could well employ over 2000 people.

Table D1-2-19 shows the breakdown of the MOX Fabrication plant unit production cost in both 1978 and 2017 dollars per kgHM. Note that this is a service or “toll” cost and does not include the cost of the fuel-grade PuO2 and UO2 powders needed as feed.

Table D1-2-19. Breakdown of Unit Production Cost for a hypothetical NOAK 480MTU/yr MOX Fab Plant



SUMMARY of ANNUAL and LEVELIZED UNIT COSTS @ Cap Rec & IDC discount rate of 3% and D&D sinking fund discount rate of 1.5%						
PWR MOX FUEL FABRICATION FROM "CLEAN" PuO2 SEPARATED PRODUCT (50 yr Plant @ 480 MTHM/yr)	1978 $ (no escalation)			2017$ (escalated)		
Life Cycle Cost Category	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution
	$M/yr	**$/kgU**	%	$M/yr	**$/kgU**	%
Capital Recovery	25.32	**52.7**	29.1%	159.59	**332.5**	38.4%
Recurring Costs incl O&M & replacements	61.14	**127.4**	70.3%	252.22	**525.5**	60.7%
D&D Sinking Fund	0.57	**1.2**	0.7%	0.57	**7.5**	0.9%
Total	87.03	**181.3**	100.0%	412.38	**865.4**	100.0%

It is observed that the “clean” MOX facility has a higher percentage of its unit cost (29%) attributable to capital recovery than the UOX plant (10%). This is due to the much higher cost for a more robust and physically larger facility producing close to the same annual amount of fuel product as the UOX plant. As with UOX; however, recurring costs still dominate the life cycle costs.

It is of interest to also consider the life cycle costs for the MOX facility requiring additional shielding of gloveboxes due to gamma-emitting radionuclides. Table D1-2-20 shows the Capital cost breakdown and Table D1-2-21 the recurring and D&D cost breakdown for 50-year plants. The assumed production is 480 MTHM/yr. Table D1-2-22 shows the unit cost breakdown compared to UOX

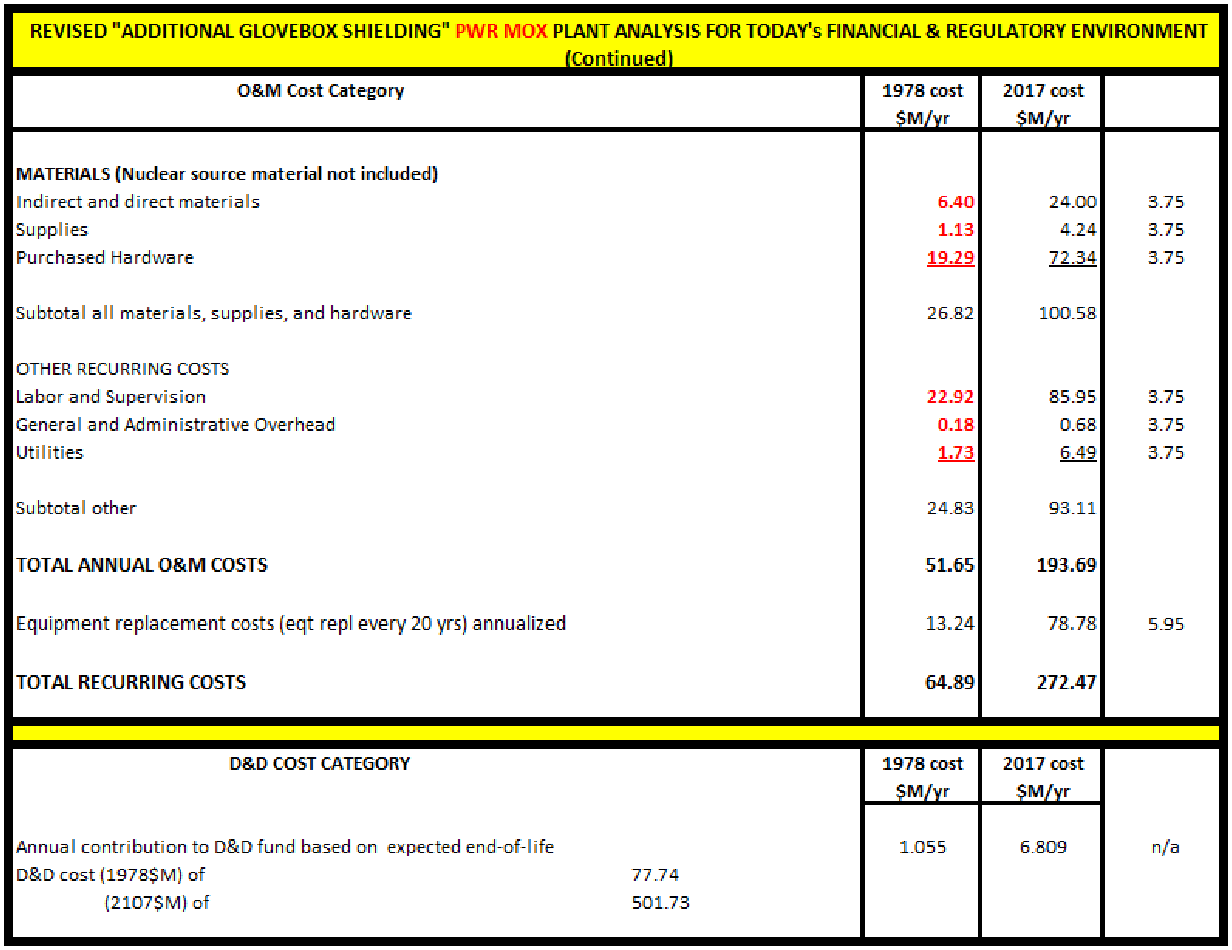
Table D1-2-20

REVISED "ADDITIONAL GLOVEBOX SHIELDING REQUIRED" PWR MOX* PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT

Capital Cost Category	Revised 1978$ cost for 50 yr plant and G4 ECONS IDC, Cap Rec, and D&D algorithms $M	2017$ cost calculated by esc index in rightmost column $M	1978$ to 2017$ Escalation factor used
BUILDINGS & CIVIL WORKS			
Process Building (incl HVAC) [more robust construction]	508.50	3417.12	6.72
Land	0.50	2.98	5.95
Site Preparation	0.50	2.98	5.95
Licensing and environmental	0.80	4.76	5.95
Security system	0.70	4.17	5.95
Office Building	1.70	10.12	5.95
Subtotal direct base cost	512.70	3442.11	
Contingency at 10% of direct costs	51.27	344.21	
Indirects including engineering at 20% of directs+ contingency	112.79	757.26	
Subtotal of contingency and indirect cost adders	164.06	1101.48	
Total Building and Civil Works Capital Cost ($M) w/o preoperations	676.76	4543.59	
PROCESS EQUIPMENT			
Base process equipment	264.73	1575.14	5.95
Contingency at 10% of base equipment cost	26.47	157.51	
Indirects including engineering at 20% of direct eqt + contingency	58.24	346.53	
Total capital equipment cost ($M)	349.44	2079.19	
TOTAL PROJECT CAPITAL COST	**1026.21**	**6622.77**	
Preoperational costs (a capitalized Owner's cost)	37.74	224.55	5.95
TOTAL CAPITAL BEFORE INTEREST DURING CONSTRUCTION (aka Overnight Cost)	**1063.95**	**6847.33**	
Interest during construction based on S-curve algorithm	117.16	754.04	
TOTAL CAPITAL COST TO BE RECOVERED	**1181.11**	**7601.37**	

* MOX fabbed from PuO2 where Pu-236 and Pu-241 decay products have had time to build-in or trace FPs are present, either requiring additional personnel protection during operations and maintenance; 50-year capital recovery & operating life, 480 MTU/yr ave production; robust process bldg; process building area of 543,519 ft2

Table D1-2-21

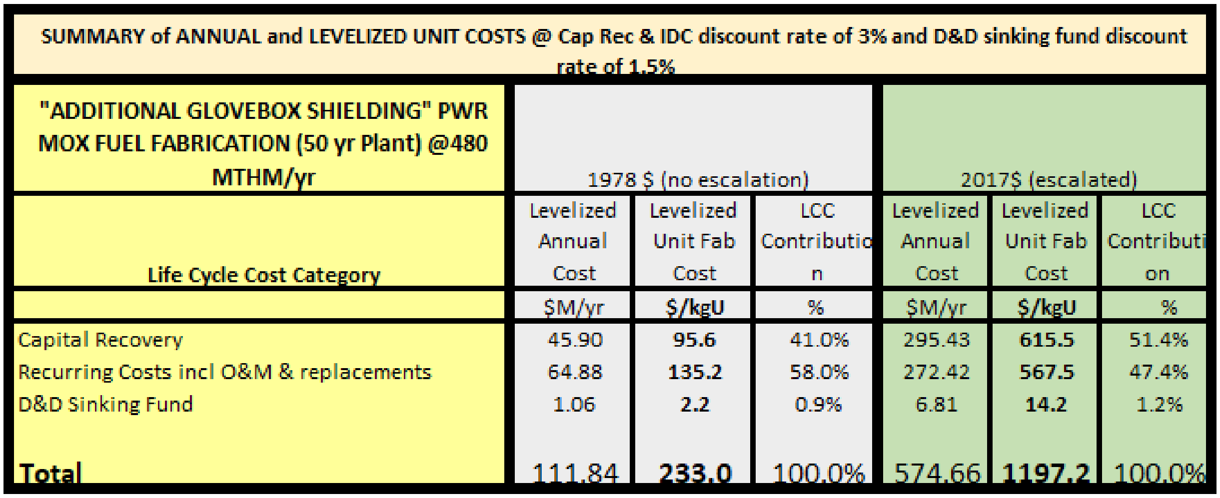


REVISED "ADDITIONAL GLOVEBOX SHIELDING" PWR MOX PLANT ANALYSIS FOR TODAY's FINANCIAL & REGULATORY ENVIRONMENT (Continued)

O&M Cost Category	1978 cost $M/yr	2017 cost $M/yr	
MATERIALS (Nuclear source material not included)			
Indirect and direct materials	6.40	24.00	3.75
Supplies	1.13	4.24	3.75
Purchased Hardware	19.29	72.34	3.75
Subtotal all materials, supplies, and hardware	26.82	100.58	
OTHER RECURRING COSTS			
Labor and Supervision	22.92	85.95	3.75
General and Administrative Overhead	0.18	0.68	3.75
Utilities	1.73	6.49	3.75
Subtotal other	24.83	93.11	
TOTAL ANNUAL O&M COSTS	**51.65**	**193.69**	
Equipment replacement costs (eqt repl every 20 yrs) annualized	13.24	78.78	5.95
TOTAL RECURRING COSTS	**64.89**	**272.47**	

D&D COST CATEGORY	1978 cost $M/yr	2017 cost $M/yr	
Annual contribution to D&D fund based on expected end-of-life D&D cost (1978$M) of 77.74 (2107$M) of 501.73	1.055	6.809	n/a

Table D1-2-22

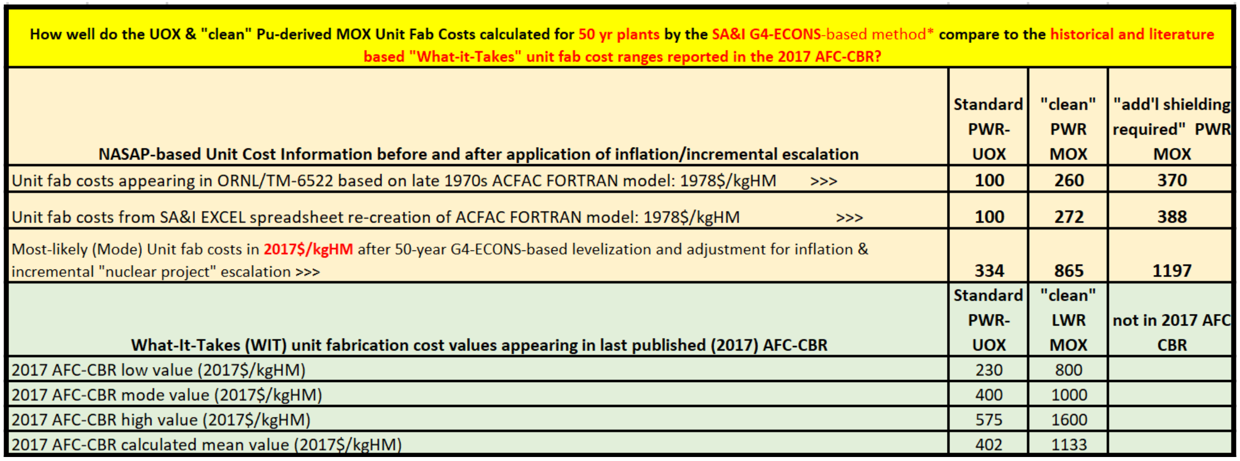


SUMMARY of ANNUAL and LEVELIZED UNIT COSTS @ Cap Rec & IDC discount rate of 3% and D&D sinking fund discount rate of 1.5%

"ADDITIONAL GLOVEBOX SHIELDING" PWR MOX FUEL FABRICATION (50 yr Plant) @480 MTHM/yr	1978 $ (no escalation)			2017$ (escalated)		
Life Cycle Cost Category	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution	Levelized Annual Cost	Levelized Unit Fab Cost	LCC Contribution
	$M/yr	**$/kgU**	%	$M/yr	**$/kgU**	%
Capital Recovery	45.90	**95.6**	41.0%	295.43	**615.5**	51.4%
Recurring Costs incl O&M & replacements	64.88	**135.2**	58.0%	272.42	**567.5**	47.4%
D&D Sinking Fund	1.06	**2.2**	0.9%	6.81	**14.2**	1.2%
Total	111.84	**233.0**	100.0%	574.66	**1197.2**	100.0%

Table D1-2- 23 shows how the calculated unit fabrication costs for all three cases (1 UOX and 2 MOX) fit within the “What-It-Takes” ranges reported in the 2017 AFC-CBR. Both results are just below the reported AFC-CBR “mode” or “most likely” values.

Table D1-2- 23. Comparison of 50-year UOX and MOX Fabrication Plant Unit Costs to Data in Present (2017) AFC-CBR

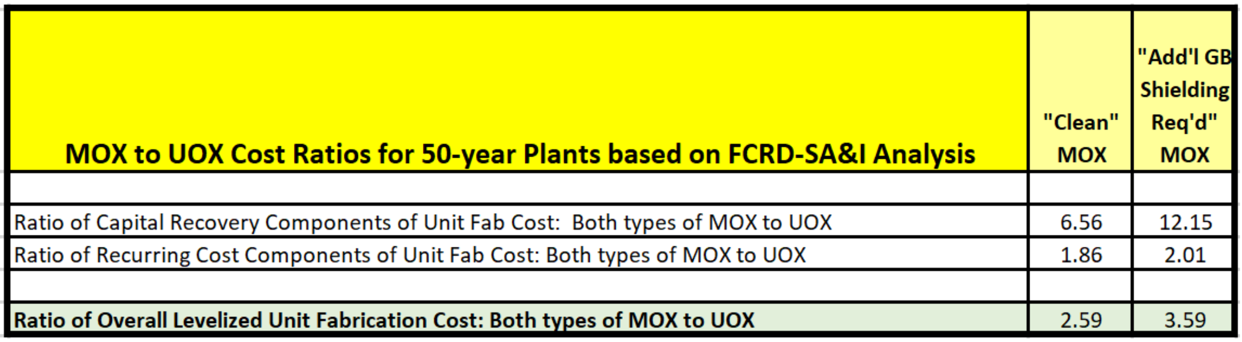


How well do the UOX & "clean" Pu-derived MOX Unit Fab Costs calculated for 50 yr plants by the SA&I G4-ECONS-based method* compare to the historical and literature based "What-it-Takes" unit fab cost ranges reported in the 2017 AFC-CBR?

NASAP-based Unit Cost Information before and after application of inflation/incremental escalation	Standard PWR-UOX	"clean" PWR MOX	"add'l shielding required" PWR MOX
Unit fab costs appearing in ORNL/TM-6522 based on late 1970s ACFAC FORTRAN model: 1978$/kgHM >>>	100	260	370
Unit fab costs from SA&I EXCEL spreadsheet re-creation of ACFAC FORTRAN model: 1978$/kgHM >>>	100	272	388
Most-likely (Mode) Unit fab costs in 2017$/kgHM after 50-year G4-ECONS-based levelization and adjustment for inflation & incremental "nuclear project" escalation >>>	334	865	1197
What-It-Takes (WIT) unit fabrication cost values appearing in last published (2017) AFC-CBR	**Standard PWR-UOX**	**"clean" LWR MOX**	**not in 2017 AFC CBR**
2017 AFC-CBR low value (2017$/kgHM)	230	800	
2017 AFC-CBR mode value (2017$/kgHM)	400	1000	
2017 AFC-CBR high value (2017$/kgHM)	575	1600	
2017 AFC-CBR calculated mean value (2017$/kgHM)	402	1133	

Table D1-2.24 shows how the unit cost breakdown for both types of MOX compare to the same categories for UOX. It can be seen that the physically larger “clean” MOX plant and “extra-shielding” MOX plant capital costs (including financing) are over six times and twelve times respectively of that of a UOX facility of a slightly larger production capability. (520 MTHM/yr for UOX and 480 MTHM/yr for both MOX cases). Totaled recurring costs for MOX such as personnel, materials, utilities, and replacements are both close to twice those for UOX. Since these costs occur for 50 years, they tend to weight the total life cycle MOX to UOX unit cost ratios as measured by the levelized unit fabrication cost, to a factor of 2.6 and 3.6 respectively.

Table D1-2-24. Comparison of MOX Unit Cost Breakdown to that of UOX

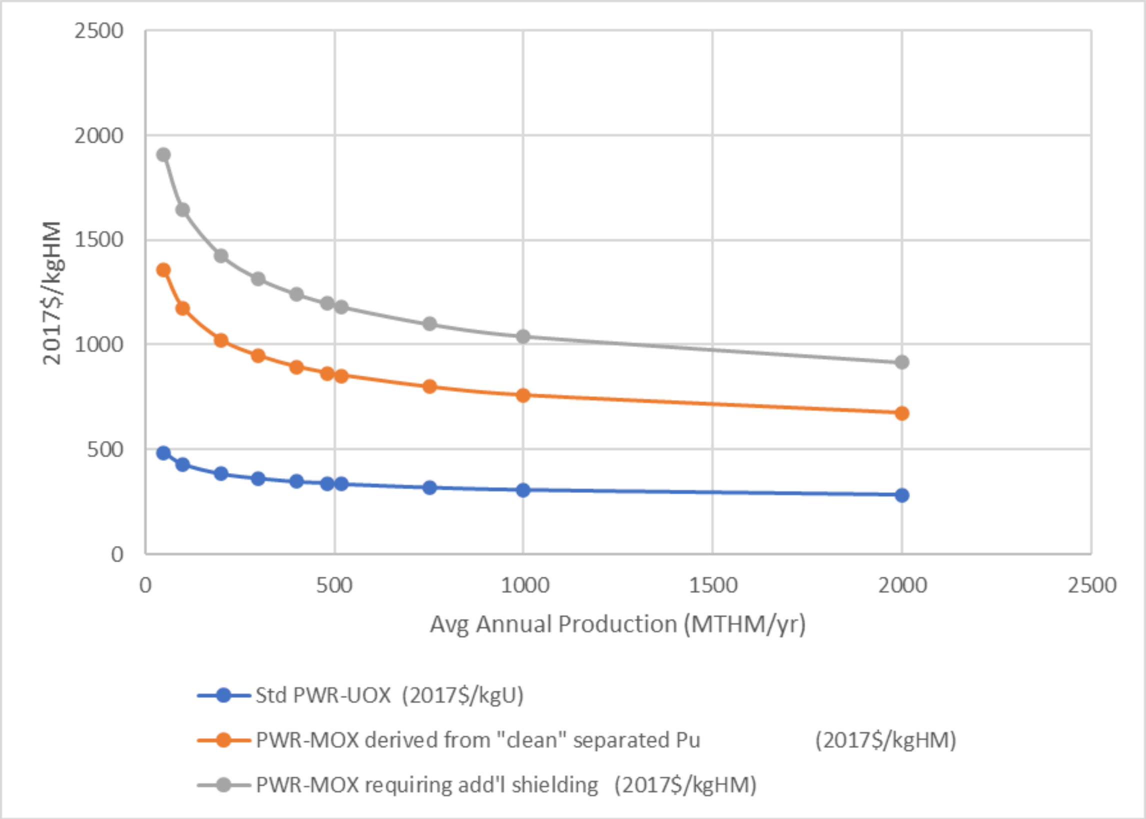


MOX to UOX Cost Ratios for 50-year Plants based on FCRD-SA&I Analysis	"Clean" MOX	"Add'l GB Shielding Req'd" MOX
Ratio of Capital Recovery Components of Unit Fab Cost: Both types of MOX to UOX	6.56	12.15
Ratio of Recurring Cost Components of Unit Fab Cost: Both types of MOX to UOX	1.86	2.01
Ratio of Overall Levelized Unit Fabrication Cost: Both types of MOX to UOX	2.59	3.59

D1-2-1.4 Conclusions and Observations from the UOX to MOX Cost Estimating Transition Effort:

- The calculated 50-year MOX (in 2017 USD) unit cost from the NASAP studies, of $865/kgHM for a 480 MTHM/yr “clean” plant, is somewhat below the most likely (mode) value of $1000/kgHM from module D1-2 of (AFC-CBR 2017), this latter value based on history or estimates for smaller “clean” MOX facilities. These newer results strengthen the basis of the expected value of the MOX fabrication costs, as revised in (AFC-CBR 2017).

- Considerable computational effort and text description was utilized in documenting the transition of MOX (and UOX) data from the NASAP reports. This new information is now fully incorporated in this FY-2021 update of the D1-2 module, in order to provide the reader with nearly “bottom-up” estimate quality data for MOX and UOX, which were originally prepared by the same analysts and are thus directly comparable. The details presented also inform the reader somewhat as to which process steps are the major cost drivers for both types of plants at the process flowsheet level.
- It should be concluded that it is possible to construct and operate a new, NOAK MOX facility in the US at costs that are reasonable; however, any transition to SNF recycle in the US would probably require partial recycle MOX use on a smaller scale. The intent would be to quickly transition to full recycle in SFRs. The bad experience with the much smaller (70MTHM/yr) but more complex Savannah River MOX Fuel Fabrication Facility (SRS-MFFF) should not be assumed for future facilities. This conclusion is based on the assumption that FOAK issues can be overcome, and that future MOX projects are well-managed.
- This analysis presented in this section was made for a PWR MOX plant for a Westinghouse-type fuel assembly. However, it is likely that the same analysis would also apply to BWR MOX fuel. Costs for BWR-MOX fabrication would be only slightly higher, because of a more complex fuel assembly structure, requiring more zirconium hardware, and possibly Pu-enrichment zoning and burnable poisons insertion into the fuel assembly.
- The NASAP reports also considered cost versus capacity scaling issues. Using these same NASAP algorithms and scaling exponents, the unit cost for UOX and two MOX variants are plotted against throughput in



- Figure D1-2-5. below. This information has also been included in the FY 2021 AFC-CBR Update Summary Report referencing this Module AFC-CBR.

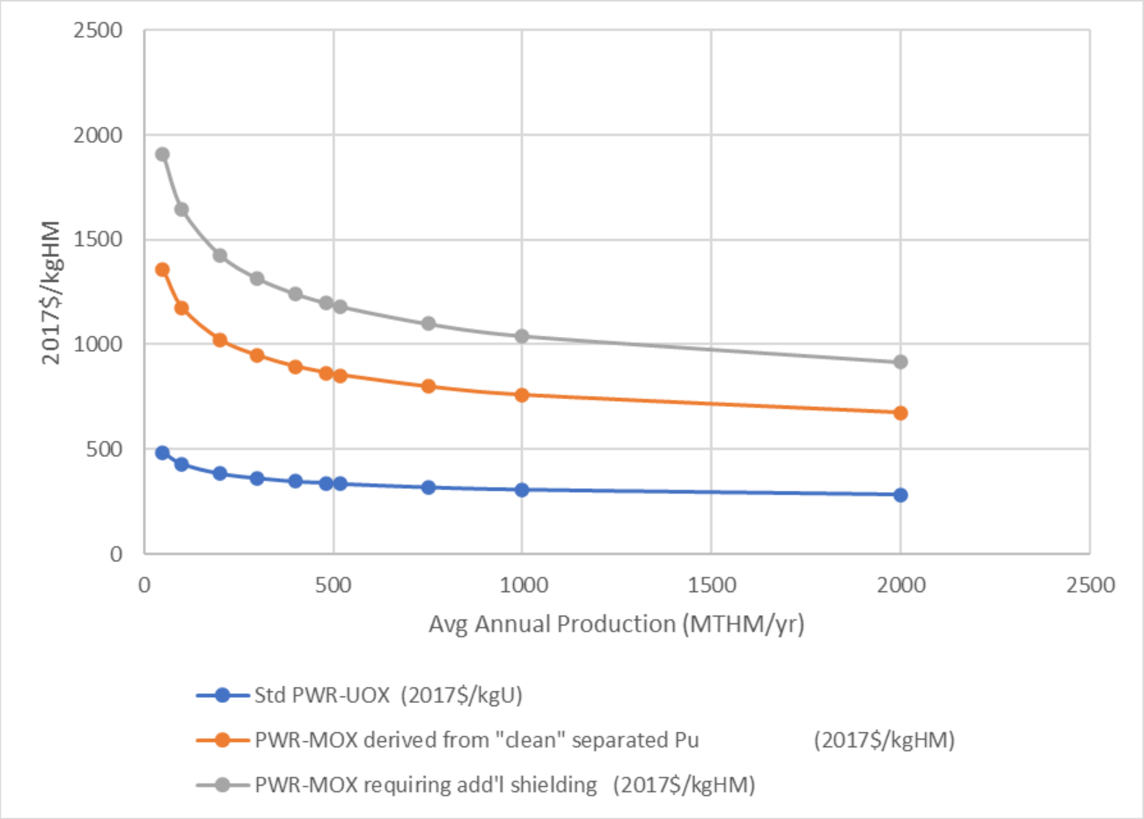


Figure D1-2-5. Sensitivity of UOX and MOX Unit Fabrication Cost to Plant Annual HM Production

D1-2.1.12 DATA LIMITATIONS

As with LEU fabrication, there is no price list for MOX fabrication. Also, there is no "spot" market for MOX fabrication services, since the product is generally non-fungible and customized to the particular reactor. (Uranium ore, conversion services, and enrichment are 'fungible" commodities that can be sold back and forth between utilities and brokers.) This means that there is no published MOX price, since most utility/fabricator contracts are proprietary.

In addition to the NASAP-informed projections most of the data presented in the earlier sections of this D1-2 module are instead based on actual plants constructed in Europe and Japan in the 1990s onward and still under interrupted construction (J-MOX in Rokkasho), never operated (ALKEM at Hanau), or operated from a brief period of time (SMP in UK). Cost data on facilities that have a substantial positive operational experience, such as the MELOX plant in France, could not be found. Consequently, there is an intrinsically high uncertainty in the estimates. The large ranges observed for the costs of MOX fabrication found in the literature, reflect the large uncertainty associated with this cost, and several high estimates may incorporate a large degree of conservativeness, mostly due to the high regulatory uncertainty. Since the estimates were calculated in the 1990s, better automation and manufacturing technology may have contributed to reduce the costs of these facilities, while an increase in safeguards, security, life safety, and physical protection requirements associated with a CAT-I facility may have contributed to an increase in the cost of a well-executed MOX fabrication plant.

Fuels that result from proliferation resistant reprocessing schemes such as UREX will contain higher actinides in the fuel, i.e., actinides such as neptunium, curium, and americium in addition to the plutonium. These additional constituents and their associated higher radioactivity will impose significant safety and operational burdens on a MOX plant (hence the name “dirty” MOX is sometimes applied). The NASAP studies addressed this possibility somewhat by present life cycle costs for a facility requiring additional glovebox shielding and remote/robotic maintenance. For MOX containing HAs with radiation fields beyond those for shielded gloveboxes a more remote “canyon” type refabrication facility would be required. The cost effects of these more stringent requirements, i.e., a requirement for totally remote-handling and direct integration with “dry” reprocessing schemes, are discussed in AFC-CBR Module F2/D2.

A major variable in the calculation of unit cost is the method of financing and ownership of the MOX facility, as well as the facility’s expected lifetime. Most of this difference is attributable to the very large carrying charges or interest associated with construction financing and plant amortization.

In summary, MOX fabrication costs and pricing are very assumption-driven, and have a high degree of uncertainty due to the very limited set of firm data on actual plants. In all cases, MOX fabrication is significantly more expensive in terms of unit per kgHM than LEU fabrication.

Some recently acquire economic studies such as (Rothwell 2015) suggest that MOX unit costs might be twice as high as the NASAP-based ones shown. The difference is due mainly to the much higher ratio of MOX to UOX personnel assumed. Rothwell suggests that even a clean MOX plant of the same size may have over seven times as many employees as a UOX plant. The subject of MOX recurring costs is certainly worth a revisit in the future.

It is also assumed in the NASAP-informed study above that no Pu polishing is required for either the clean or extra-shielding MOX plants. According to (NEA 1987) a pre-fabrication aqueous polishing step for the PuO2 blendstock would cost 10 to 28 $/gram Pu in 1987$, which in today’s 2020$ would be 35 to 97$/gPu. For MOX fuel that is 10% Pu, this translates to 3500$ to 9700$/kgHM, which is significantly higher than any fabrication cost. This fact provides incentive to utilize the PuO2 as quickly as possible after SNF reprocessing.

D1-2.1.13 COST SUMMARIES

WIT Values from previous published AFC-CBR (2017) To provide some historical perspective the 2017 AFC-CBR (Dixon et al 2017) module cost information is summarized in the What-It-Takes (WIT) cost summary in Table D1-2-25. The summary shows the reference cost basis (constant year $U.S.), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Note that this Table D1-2-25 information was developed from analysis of multiple sources prior to 2017, i.e. before the NASAP reports were found and analyzed. The new (2020) WIT information below in Table D1-2-26 benefits from the extensive life cycle cost analyses prepared for NASAP and updated by FCRD-SA&I from 2018 to 2020.

Table D1-2-25. AFC-CBR 2017 Cost summary table for commercial LWR MOX fuel fabricated from clean separated plutonium (Data not based on recasting of NASAP study).

What-It-Takes (WIT) Table (2017 constant $)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
$1,000/kgHM as reference cost for “normal” MOX	Unit=$800/kgHM	Unit=$1,600/kgHM	Unit=$1,000/kgHM

based on European experience.			
None available	Mature MOX technology in the U.S. for new facilities. Well executed project. 3% discount rate, 50 years lifetime O&M 7% of initial construction costs.	Project with some cost overruns. 10% discount rate, 30 years lifetime O&M 13% of initial construction costs.	Mature MOX technology in the U.S. for new facilities. Well executed project. 5% discount rate, 40 years lifetime O&M 7% of initial construction costs.

A triangular distribution based on the low, nominal (aka mode), and high unit fabrication costs appearing in the table above was assumed. A mean value of 1133 $/kgHM would result.

FY 2021 Updated WIT Values Resulting from the NASAP-based analyses described in this report for both 1.) U,Pu LWR MOX fabricated from clean separated plutonium in conventional alpha-protection gloveboxes and 2.) U,Pu LWR MOX prepared from separated Pu requiring additional glovebox shielding and remote/robotic maintenance. Table D1-2-26 shows the low, mode, high, and calculated mean values for the two types of U,Pu LWR MOX described in this report. The type of relative probability distribution defined by the low, mode, and high values also appears in the table. Since escalation from 1978$ to 2017$ was used for all of the 2018 SA&I rework of the NASAP studies, the year 2017 was used as the new technical basis year in Tables D1-2-26 and D1-2-27. The low and high values for each type were derived from a sensitivity analysis of unit cost versus plant annual production using scaling equations and exponents, with the low value defined by a 2000 MTHM/yr plant and the high value by a 50 MTHM/yr plant.

Table D1-2-26. FY 2021 Update “What-it-Takes (WIT) Unit Fabrication Costs for two LWR MOX fuel variants in 2017$

U,Pu LWR MOX Fuel variant	Low Unit Fab Cost in 2017$/kgHM	Mode Unit Fab Cost in 2017$/kgHM (most probable)	High Unit Fab Cost in 2017$/kgHM	Calculated Mean Unit fabrication cost (2017$/kgHM)	Distribution Type
Fuel fabricated from clean separated Pu	673	865	1359	966	Triangular
Fuel fabricated from separated Pu requiring additional glovebox shielding and remote maintenance	905	1197	1910	1341	Triangular
Avg Annual Production in MTHM/year	2000	480	50	n/a	

Table D1-2-27 below shows the same 2017$ unit cost values in Table D1-2.26 above escalated by a factor of 5.2% to 2020$ for the same two MOX fuel variants.

Table D1-2-27. FY 2021 Update "What-it-Takes (WIT) Unit Fabrication Costs for two LWR MOX fuel variants escalated to 2020$

U,Pu LWR MOX Fuel variant	Low Unit Fab Cost in 2020$/kgHM	Mode Unit Fab Cost in 2020$/kgHM (most probable)	High Unit Fab Cost in 2020$/kgHM	Calculated Mean Unit fabrication cost (2020$/kgHM)	Distribution Type
a) Fuel fabricated from clean separated Pu	708	910	1430	1016	Triangular
b) Fuel fabricated from separated Pu requiring additional glovebox shielding and remote maintenance	963	1259	2009	1410	Triangular
Avg Annual Production in MTHM/year	2000	480	50	n/a	

Figure D1-2-6 shows the relative and cumulative probability distributions, based on a triangular distribution, for the data in Table D1-2-27

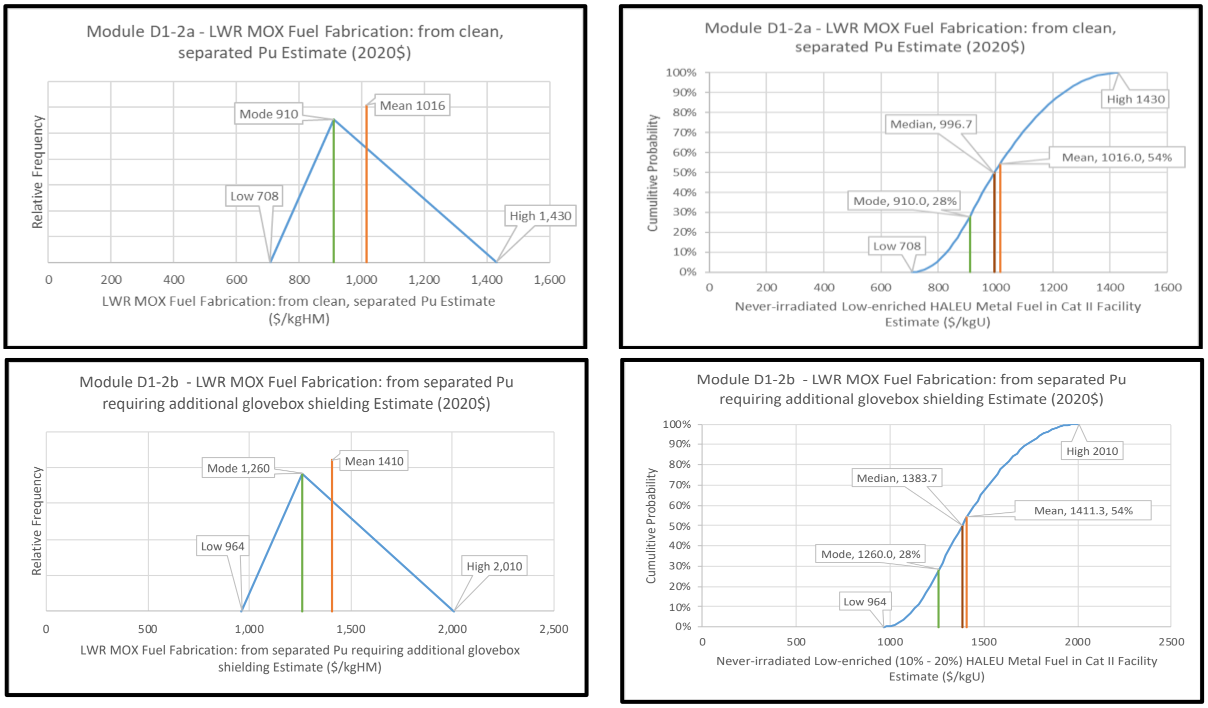


Figure D1-2-6. LWR MOX fuel fabrication estimated cost frequency distributions.

Figure D1-2-7 Yr 2020 Unit Costs for Water Reactor Fuels

Error! Reference source not found. above shows the unit costs of UOX and the LWR MOX variants compared to other water reactor fuels considered in fuel fabrication Modules D1-1 (LWR fuels), D1-7 (PHWR fuels), and D1-8 (thorium fuels).

Table D1-2-28 Additional Data on Cases Described Figure D1-2-7

Unit Cost Values (in 2020$/kgHM unless otherwise noted)	D1-7	D1-7	**D1-1**	D1-1	D1-1	D1-1	D1-1	D1-1	D1-1	D1-8	D1-8	D1-5	**D1-2**	**D1-2**
14 Variants >>	PHWR-UOX (DUO2 or NATUO2)	PHWR-UOX (Slightly-enriched REPUOX)	Virgin PWR-UOX	Refab Reprocessed & Re-enriched PWR UOX (REPU)	Virgin BWR UOX	Refab Reprocessed and re-enriched BWR UOX (REPU)	LWR ATF: Zr-clad UO2 with coating or SiC clad	LWR: ATF: Zr-clad U3Si2 with coating or SiC clad	LWR ATF: Zr-clad UN with coating or SiC coating	Thoria (ThO2) blanket pellets for LWR	LWR ATF: HALEU-Th MOX (Fab)	PWR U,Pu VIPAC MOX (Fab)	PWR-U,Pu pelletized MOX (Fab)	PWR-U,Pu pelletized MOX (Refab)
WIT High	324	386	605	666	605	666	787	889	1155	723	861	1287	1430	2009
WIT Mode	209	257	351	387	351	387	529	520	685	515	603	819	910	1259
WIT Low	174	206	242	266	300	330	271	366	408	287	344	637	708	963
WIT mean unit fab cost for triangular distribution	235	283	399	440	419	461	529	592	749	508	602	914	1016	1410
1978$ reference value for fuel in NASAP reports	60	fuel variant not covered in NASAP study	100	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	fuel variant not covered in NASAP study	110	fuel variant not covered in NASAP study	260	370
Ratio of 2020$ WIT mean unit cost to NASAP reference 1978$ unit cost	3.92	---	3.99	---	---	---	---	---	---	---	5.47	---	3.91	3.81
Facility Type based on fissile material attractiveness criteria	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-III	CAT-II	CAT-I	CAT-I	CAT-I

D1-2.1.14 SENSITIVITY AND UNCERTAINTY ANALYSES

The sensitivity of unit fabrication cost to facility average annual production is presented in Section D1-2.7 above.

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