Advanced Fuel Cycle Cost Basis Report: Module D1-7 Contact-Handled Pelletized Pressurized Heavy-Water Reactor (PHWR) UOX 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 this module first appeared: 2004 as Module D1-7. In 2005, a special section on the direct use of plutonium in CANDU (DUPIC) concept was added. The DUPIC discussion, based on information from a paper by Choi et al. (2001), was moved in the 2017 AFC-CBR to Module D2 as a special topic. The DUPIC reprocessing/refabrication process requires remote handling, thus the discussion will be moved to the forthcoming Module F2/D2 in the 2021 AFC-CBR update. In 2012, the AFC-CBR Module unit costs of CANDU fuels fabricated from reprocessed uranium were added. This pelletized pressurized heavy-water reactor (PHWR)-REPUOX what-it-takes data is also updated in this module.
	2012	All	Latest version of module in which new technical data was used to establish unit cost ranges: 2012 prior to this report.
		All	New technical/cost data which has recently become available and will benefit next revision: • CANDU PHWR fuels with thorium added to the uranium, such as ANEEL, are being seriously considered (NEI 2021) • CANDU PHWR fuels fabricated from reprocessed uranium is being slated for use in Chinese PHWRs.
	2021	All	Reformatted 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 U.S. dollars (USD or $) of year 2020.

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ACKNOWLEDGEMENT

This latest version of the *Module D1-7: Contact-handled Pelletized Pressurized Heavy-Water Reactor (PHWR) UOX Fuel Fabrication* is the cumulative effort of many authors who have contributed to the *Advanced Fuel Cycle Cost Basis Report*. It is not possible to identify and acknowledge all those contributions to the report and this module. All the authors, including the four primary authors, 15 contributing authors, the 12 contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. Jason Hansen (Idaho National Laboratory, jason.hansen@inl.gov) and Edward Hoffman (Argonne National Laboratory, ehoffman@anl.gov) can be contacted with any questions regarding this document.

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ACRONYMS

ACR	Advanced CANDU Reactor
AECL	Atomic Energy of Canada Limited
AFC-CBR	Advanced Fuel Cycle Cost Basis Report
ANEEL	Advanced Nuclear Energy for Enriched Life (advanced Th/HALEU PHWR fuel)
BWR	boiling-water reactor
CANDU	Canadian Deuterium Uranium (reactor)
CM	contact maintenance
CPI	cost-of-living aka consumer price index
CRF	capital recovery factor aka fixed charge rate
D&D	Decontamination and decommissioning
DUPIC	Direct Use of Plutonium In CANDU
EMWG	Economic Modelling Working Group (GIF)
EOL	End-of-life
EPRI	Electric Power Research Institute
ES&H	Environment, safety, and health
FC	fuel cycle
FOAK	first-of-a-kind
FTE	full-time equivalents
G4-ECONS	Generation IV EXCEL Calculation of Nuclear Systems
GIF	Generation IV Reactors International Forum
GNF	Global Nuclear Fuels
HALEU	high-assay, low-enriched uranium
HEU	highly enriched uranium
HF	hydrofluoric acid
HS&E	health, safety, and environmental
HVAC	heating and ventilation, and air conditioning
HWR	heavy-water reactor
IDC	interest during construction
IPD	implicit price deflator
LCC	life cycle cost
LEU	low-enriched uranium
$LEUF_6$	low-enriched uranium hexafluoride
$LEUO_2$	low-enriched uranium dioxide

LUEC	levelized unit electricity cost
LWR	light-water reactor
MOX	mixed (uranium and plutonium) oxide fuel
MTHM	metric tons of heavy metal
MTU	metric tons of uranium
MW(th)	megawatts thermal
NASAP	Nonproliferation Alternative Systems Assessment Program
NATU	natural uranium
NATUOX	natural assay uranium oxide (aka NATUO2)
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PHWR	pressurized heavy-water reactor
Pu	plutonium
PWR	pressurized-water reactor
QA	quality-assurance
QC	quality control
ROI	return to investors
RU aka REPU	reprocessed uranium
SA&I	systems analysis and integration
SEU	slightly-enriched uranium
$SEUF_6$	slightly-enriched uranium hexafluoride
SEUOX	slightly-enriched uranium oxide (aka SEUO2)
SNF	spent nuclear fuel
SWU	separative work units
TCC	total financing inclusive capital cost
TEC	total capital cost
TM	technical memorandum
TRL	technical readiness level
TRU	transuranic waste
UO_2	uranium dioxide
UOX	uranium oxide

USAEC	United States Atomic Energy Commission
USNRC	United States Nuclear Regulatory Commission
WIT	what-it-takes
WNA	World Nuclear Association

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MODULE D1-7 CONTACT-HANDLED PELLETIZED PRESSURIZED HEAVY-WATER (PHWR) UOX FUEL FABRICATION

SHORT DESCRIPTION OF METHODOLOGY USED FOR THE ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant U.S. Dollar (USD or $) Base Year 2020 for this Fiscal Year (FY) 2021 Update.**
- **Nature of this 2021 Module Update from Previous Advanced Fuel Cycle Cost Basis Reports (AFC-CBRs):** In addition to literature-based pressurized heavy-water reactor (PHWR) fuel price information in the 2017 AFC-CBR, the what-it-takes (WIT) unit cost data in this update is informed by new analysis and escalation of the 1978 PHWR-UOX fuel life cycle cost (LCC) data from ORNL reports prepared for the 1977–1980 Nonproliferation Alternative Systems Assessment Program (NASAP). (These reports are referenced and summarized in detail in Module D1-PR.) The PHWR fuel fabrication LCC data in these reports is scaled from a bottom-up cost estimate for a reference technology pressurized-water reactor (PWR)—uranium oxide (UOX) fuel fabrication plant by using algorithms that consider the manufacturing process complexity, fuel design complexity, plant floor space requirements, and the radiation and health, safety, and environmental (HS&E) regulatory environment of PHWR-UOX fuel production vis-à-vis light-water reactor (LWR)-UOX production (PWR fuel in this case). The module name has been changed from "Canadian Deuterium Uranium (CANDU)" to the more generic PHWR fuel fabrication in recognition that not all power reactors that might use this fuel type are considered. Unfortunately, the detailed algorithms and their design bases were not archived at the end of the NASAP effort of the commercial CANDU concept specifically developed in the middle of the last century by Atomic Energy of Canada Limited (AECL).
- **Estimating Methodology for Latest Technical Update Which this Update Was Escalated:** In January 2021, the PHWR fabrication costs were reassessed based on NASAP LCCs described above and documented in this report. All NASAP-based fuel studies to date are based on the conversion of 1978 detailed life cost data, derived from a bottom-up estimate for the PWR-UOX modified by algorithms to accommodate other fuel types, to today's economic environment and 2020 USD. Levelized unit fabrication costs are calculated using the G4-ECONS EXCEL-based algorithms developed by the Generation IV Reactor Forum's Economic Modelling Working Group in 2007. An escalation factor of 5.2% is used to convert 2017 USD to 2020 USD. This is basically same rationale as for LWR-UOX fuels in Module D1-1.

D1-7.1. BASIC INFORMATION

2021 AFC-CBR Status. Because the advanced CANDU ACR-700 (Advanced CANDU Reactor) Generation III+ heavy-water reactor (HWR) design at one time started the Nuclear Regulatory Commission (USNRC) certification in the United States, and it is also being offered for sale on the international market, it is useful to briefly consider the projected manufacturing cost for PHWR fuel and that of its other CANDU reactor cousins. (Reactor Module R5 of the AFC-CBR discusses PHWRs based on the CANDU design.) PHWR fuel is manufactured in several locations worldwide with the largest fuel fabrication facilities in Canada, India, and Korea. Table D1-7.1 from the World Nuclear Association website (WNA 2019) shows the locations and production capacities of these facilities.

Table D1-7.1. Locations and production capacities of PHWR fuel fabrication facilities (rod/assembly column units are annual production in MTU/year) (WNA 2019).

Fabricator		Location	Rod/Assembly
Argentina	CONUAR	Cordoba & Ezeiza	160
Canada	Cameco	Port Hope	1,500
	BNF-Canada	Toronto Peterborough	1,500
China	CNNFC	Baotou	246
Pakistan	PAEC	Chashma	20
Korea	KEPCO	Taejon	400
Romania	SNN	Pitesti	250
Total	–	–	**5076**

CANDU-PHWR fuel is fabricated in the largest quantities in Canada by two firms in the Province of Ontario: Global Nuclear Fuels (GNF) Canada and Cameco Fuel Manufacturing (formerly Zircatec). Figure D1-7.1 shows an aerial view of the Cameco facilities at Port Hope, Ontario with the PHWR fabrication plant in the foreground and a uranium (U) ore, also known as yellowcake, to UF_6 conversion plant in the background.

Figure D1-7.1. Cameco facilities at Port Hope, Ontario, Canada.

Presently, generation CANDU fuel is not made from enriched U, hence no UF_6-based enrichment step is needed in the front-end fuel cycle (FC). Since no enrichment plant depleted U tails, considered a waste product, are produced in this once-through FC, the PHWR has a higher U utilization (from mined U) than much higher burnup LWRs. Table D1-7.2 shows some data on fuel consumption by PHWRs.

Table D1-7.2. Fuel consumption data for a typical CANDU-type PHWR.

Reactor Net Electrical Capacity (e.g., Darlington, ON)	881 MWe
Reactor Gross Electrical Capacity (e.g., Darlington, ON)	935 MWE
Reactor Thermal Capacity (e.g., Darlington, ON)	2,778 MWth
Reactor Average Capacity Factor	85%
Annual Natural Uranium (NATU) Usage	117 MTU/yr
Core Average Fuel Burnup	8,330 MWt-days/MTU
CANDU-PHWR Reactors of This Capacity Supplied by a 520 MTU/yr Fabrication Facility (NASAP-based Reference Plant Described Later in This Module for Life Cycle Costing)	4.4

Figure D1-7.2 shows the basic fabrication process for PHWR-UOX fuel (aka HWR fuel). The flowsheet is very similar to that for ceramic pelletized LWR-UOX fuels. Note that the Oak Ridge National Laboratory (ORNL)/NASAP Figure D1-7.2 shows the generic flowsheet applies to possible PHWR mixed oxide fuels containing PuO_2 or ThO_2 in addition to UO_2. Use of some of these more advanced types of mixed (U and Pu) oxide fuel (MOX) fuel for some PHWRs is still under consideration, particularly in China. Some of these developments are discussed below; however, only all-UOX fuels are considered in depth in this Module D1-7.

Note that the higher purity spec-powder NATU oxide (UO_2) feed required by the PHWR fuel fabricator for pelletization (early steps in Figure D1-7.2) can be prepared in a U_3O_8 to UO_3 to UO_2 facility adjacent to the raw ore to U_3O_8 milling facility (natural UO_2 can be used for fuel in a PHWR by virtue of the reactor's heavy-water moderator/coolant). Nearly all the world's CANDU PHWRs use this natural UOX fuel. The newer-type CANDU ACR-700 CANFLEX fuel, however, will be slightly enriched U (SEU) at around 2% U-235. Its fuel assembly and the older CANDU NATUO2 fuel assemblies, however, do not at all look like an LEU-LWR fuel assembly. The fuel assemblies are much shorter but still use stacked UO_2 pellets in horizontal tubes (Figure D1-7.3).

As for pelletized LWR fuel (Module D1-1), a mature industry exists to produce CANDU reactor fuel from virgin NATU. GE-Hitachi Canada Ltd. (aka GNF) at one time produced up to 1,800 MTUO2/yr of NATU-CANDU fuel, and this operation at both Peterborough and Toronto, Ontario has been taken over by BWX Technologies, Inc. For this fuel vendor, two facilities in Ontario are used: the Toronto facility for UO_2 pellet production and the Peterborough facility for fuel bundle production. The relicensing of these facilities to produce SEU (slightly enriched 1 to 2.5% U-235) CANFLEX fuel for advanced CANDU reactor designs is under consideration by Canadian nuclear safety authorities.

A recent development regarding CANDU fuel use is that China is considering a large-scale use of reprocessed U (RU) from LWR spent fuel reprocessing as a natural U (NATU)-substitute fuel for their fleet of CANDU reactors (Ellis 2007; Chen 2011). This reprocessing-derived material has U-235 enrichments in the 0.6 to 1.0% range (typically blended to ~0.9% U-235) a suitable substitution for NATU or SEU. The REPU (reprocessed uranium or RU) could come from Russian, European, or Japanese sources of stored reprocessed U. Ultimately China will also have their own LWR spent fuel reprocessing industry which can provide this feed material. If the United States were to ultimately reprocess LWR spent nuclear fuel (SNF), CANDUs could provide an excellent use for the large amounts of resultant RU.

The use of (U, Th) O_2 pellets is also being considered in CANDU-type fuel. Thorium-based fuels are discussed in Module D1-8.

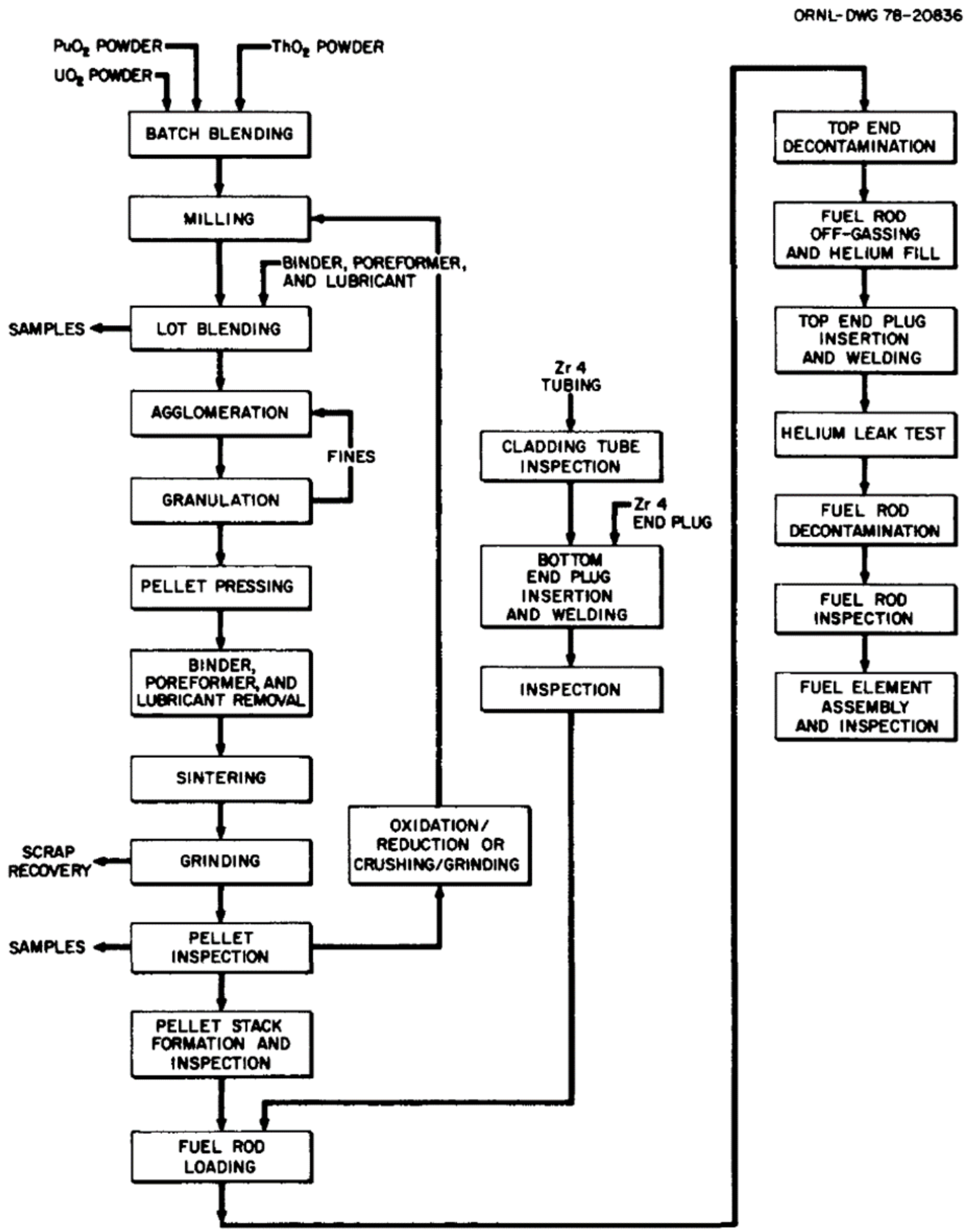

Fig. 9. HWR oxide recycle fuel element fabrication flowsheet.

Figure D1-7.2. Basic process flowsheet for PHWR-UOX fuel production (from ORNL/TM-6640, Judkins and Olsen 1979b) includes all possible nuclear material feed types including mixed oxides. Note regarding flowsheet, a different zirconium alloy, Zr2.5Nb, is used for today’s CANDU fuels.

D1-7.2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

Basic Plant Configuration. A PHWR-UOX CANDU fuel bundle (assembly) still uses pelletized ceramic UO_2 fuel; so, most of the pellet and rod loading manufacturing process steps are the same as for LWR-UOX fuel. Because the fuel bundle is an order of magnitude shorter and lighter than LWR fuel, the process building floor space per kilogram of fuel for metallurgical operations is smaller; however, post-pellet steps of the manufacturing process are similar in complexity. Batch size control and criticality concerns are minimal to nonexistent in CANDU fuel fabrication plants as compared to LEU PWR-UOX and boiling-water reactor (BWR)-UOX fuel fabrication plants.

CANDU reactors can also be operated on plutonium-bearing MOX fuel. AECL has irradiated some weapons-derived MOX fuel in their experimental HWR at Chalk River, Ontario. This PARALLEX MOX project with Russia and the United States was part of the 1996–2017 joint U.S./Russian Federation Plutonium Disposition Program. A glovebox-type contact-handling plant that would produce production quantities of CANDU MOX fuel would be nearly identical to fuel fabrication plants producing PWR or BWR-MOX fuel, except that the resulting PHWR-MOX final fuel assembly form would be much smaller than and would appear the same as PHWR-UOX CANDU fuel.

D1-7.3. PICTURES AND DIAGRAMS

Figure D1-7.3 shows an ACR-700 assembly, which like all CANDU fuel variants resides in the reactor horizontally rather than vertically. Each parallel tube is filled with ceramic oxide pellets. The assemblies are fed continuously to the pressure-tube type reactor while it is running rather than in reload batches during shutdowns per the LWR. Figure D1-7.4, from ACR data submitted to the USNRC (AECL 2005), shows this refueling operation.

Figure D1-7.3. The ACR-700 CANDU fuel assembly aka bundle (AECL 2005).

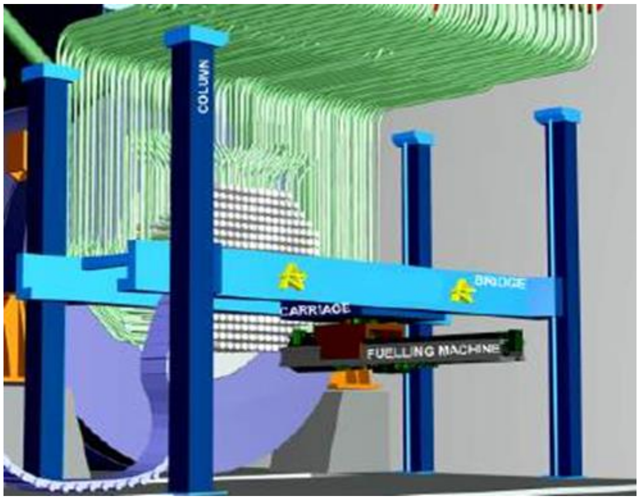

Figure D1-7.4. Horizontal on-line refueling for the ACR-700 CANDU reactor (AECL 2005).

Table D1-7.3 shows some late 1970s PHWR fuel bundle design data from the NASAP study which is still descriptive of the fuel bundles in today's operating CANDU NATUOX-fueled PHWRs.

Table D1-7.3. PHWR fuel bundle data (typical).

Bundle length	19.5 in. (~0.5 m)
Bundle diameter	10 cm
Metal structure content	Zirconium-niobium alloy
Fuel pins per bundle	37
Gross mass of bundle	24.8 kg
Heavy metal mass of bundle	20 kgU
Pellet diameter	14.4 mm
U-235 content of UO_2	0.71 wt %

D1-7.4. MODULE INTERFACES

Front-End Interfaces. A CANDU fuel fabrication plant preparing slightly enriched UO_2 ACR 700 fuel (SEU) will require enriched UF_6 deconversion ($LEUF_6$ to $LEUO_2$) before the pellet preparation steps. For present generation CANDU reactor fuel, which is NATU, the reactor-grade sinterable UO_2 powder can be prepared from final ore milling steps (AFC-CBR Module A1) rather than as a separate front-end chemical deconversion step in the PHWR fuel fabrication plant. The initial yellowcake or impure U_3O_8 form produced in the mill will need a later purification step at the same mill to remove small amounts of chromium, vanadium, and other metals (carried over from the ore) from the U oxide feed form before shipping to the PHWR fabrication plant as UO_3 or UO_2. (As for LWR-UOX fabrication, the pellet product from the first steps of the PHWR-UOX fabrication plant has very stringent purity standards for charging to a reactor, hence the need for very clean reactor-grade natural UOX powder feed.) A dry UF_6 based purification process or a wet process is required for this separation of U from trace metals. UO_3 from either process must be hydrated and steam-reduced to produce pure UO_2 powder of the proper morphology. Note that in LWR-$LEUO_2$ fabrication, this "purification" step is accomplished by the U_3O_8 to UF_6 conversion step (Module B), to some degree in the enrichment cascade (Module C1), and in the front-end $LEUF_6$ to UO_2 deconversion step of LEU-UOX fabrication (Module D1-1).

Finished NATUO2 CANDU fuel bundles are shipped in conventional cartons to the reactor sites. Criticality safety is not a concern for NATU at the throughput levels of interest here and in any unmoderated storage conditions. The ACR-700 EUO_2 (SEU) fuel may require a certified shipping package as does LEU-LWR fuel in the United States.

Back-End Interfaces. CANDU-PHWR reactors have larger cores than LWRs of the same power capacity. Volume-wise, there will be significantly more SNF that needs to be stored and ultimately disposed by geologic repository emplacement. Reprocessing requirements would be similar to those for UO_2 LWR fuels.

D1-7.5. SCALING CONSIDERATIONS

The same observations on fabrication plant scaling apply for this type of fuel as for LWR fuel (Subsection D1-1.5 of Module D1-1). In a later section of this report, a unit fabrication cost versus PHWR-UOX production throughput curve will be presented.

D1-7.6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

This section is basically divided into two parts: (1) a description of any PHWR-UOX cost or price data obtained from literature sources, which also contains a recap of the unit cost data in previous versions of the AFC-CBR, and (2) new PHWR-UOX fuel fabrication LCC data from the 1977–1980 NASAP fuel fabrication study conducted by the Metals and Ceramics Division of ORNL and documented in multiple reports as listed in Module D1-PR in this document.

D1-7.6.1Literature-Based Cost Data from Previous Reports

2009 AFC-CBD Data. Assuming the manufacturing/fabrication process for the newer SEU fuel assembly is the same as for past CANDU NATU assemblies, the unit cost should be similar. This will be true as long as the SEU U-235 enrichment level stays low enough that nuclear criticality in the manufacturing process is not an issue. If the 1991 NATU value from the NEA/OECD FC study (OECD NEA 2006) is escalated to 2009 constant USD, a fabrication cost of $~105/kgU results. A conversion cost should be added to this for slightly enriched EUF_6 to ceramic-grade UO_2 powder, a step that is not needed for NATU-CANDU fuels. The author of this report assumed that $30/kgU cost adder (in 2009 USD) would be appropriate for a total cost of $135/kgU. This is significantly smaller than for LWR fuel; however, the CANDU-PHWR-UOX fuel assembly/bundle is simpler by design, and no criticality monitoring and controls during manufacturing exist.

Fabrication costs for CANDU MOX fuels, either $(U,Pu)O_2$ or $(U,Th)O_2$, would be expected to be in the lower end of the ranges for LWR MOX fuels as presented in Fuel Fabrication Modules D1-2 and D1-8. ANEEL-type CANDU fuels (NEI 2021) containing both thorium and high-assay, low-enriched U (HALEU) would have higher unit cost because of the high unit cost of HALEU (see Module C3 for HALEU cost information).

2012 AFC-CBD Update Data. Like LWR fuel fabricators, the Canadian and other nations' CANDU fuel fabricators do not publish information regarding costs of fuel production or publish prices received for finished fuel bundles because of similarities in (1) production methodology, (2) Canadian vis-à-vis U.S. regulations, (3) quality-assurance (QA) requirements, and (4) fuel cladding materials (zirconium and zirconium alloys). However, the same factors affecting LWR fuel fabrication from 2009 to 2012 will also affect PHWR-CANDU fuel. In Module D1-1, the nominal fuel fabrication unit cost was increased by 40% in 2012 to account for these factors, which included a rising price of reactor-grade zirconium. If the same 1.4 factor is applied to the 2009 AFC-CBD CANDU fuel unit cost value of 135 $/kgU, a nominal value of 189 $/kgU (2012 USD) results.

One can also use the complexity factor (subject fuel technology unit cost divided by PWR fuel unit cost) from (Olsen et al. 1979), a 1979 ORNL-NASAP report comparing several large-plant fuel fabrication technologies on a level-playing field basis. If the factor of 0.59 (for PHWR-NATU fuel) is applied, a unit cost of $207/kgU results when applied to the $350 $/kgU nominal values from the first line of the D1 LWR-UOX option in summary Table S-1 of the 2012 AFC-CBR, or from Table D1-1.2 in Submodule D1-1 of the 2012 AFC-CBR. A more extensive review and use of the late 1970s NASAP PHWR LCC data (Olsen et al 1979) by SA&I in 2021will be discussed below.

If RU or REPU from LWRs is used in CANDUs, the CANDU fuel fabricator will face the same environment, safety, and health (ES&H) issues arising from U-232, U-236, and fission product impurities that would affect an LWR fuel fabricator. The additional costs would result in a unit cost penalty for RU use. An EPRI report (Electric Power Research Institute 2010) has an analysis which utilizes a 30% increase from the conventional unit cost of fabricating CANDU fuel arising from virgin NATU. Even with this fuel fabrication cost increase, the overall cost (FC cost in $/MWh generated) of the front end of an open CANDU FC using LWR-RU can be lower than for a FC using virgin NATU. The savings are due to not having to purchase and process new U ore (U_3O_8).

D1-7.6.22021 AFC-CBR Data Derived from Detailed Life Cycle Cost Data from the Late 1970s ORNL-NASAP Study.

D1-7.6.2.1 Starting Point for 2021 SA&I Calculation of New Unit Cost Data

A new unit cost for PHWR-UOX fuel fabrication is derived from a 1978 bottom-up LCC estimate for a PWR-UOX fuel fabrication facility. In this subsection, NASAP-derived, detailed PHWR LCC data (rather than market price information) will be presented and utilized for determining WIT PHWR fuel fabrication unit costs. Such levelized unit-cost information more realistically represents the true value-added in converting clean natural UOX powder from a mill to a fuel bundle product ready for charging to a commercial CANDU-type reactor. If LCC includes financing costs, as often represented by a discount rate or a return to investors (ROI), a profit is essentially covered in the calculated, levelized unit cost of fabricated fuel product. In an equilibrium market free of significant oversupply or undersupply, this unit fabrication cost can be said to represent a unit price where price-based revenues to the facility owner cover all costs including a return on investment.

D1-7.6.2.2 Limitations of Cost or Price Data Prior to Use of ORNL-NASAP Data

As mentioned earlier, fuel fabrication pricing is based on the provision of a manufacturing service for what is essentially a somewhat custom-made UOX fuel assembly, also known as bundle, designed for a particular PHWR vendor’s reactor model number and specific utility requirements, such as irradiation exposure time and desired fuel burnup. (Basically, this is the same situation as with LWR fuel; however, there are far fewer PHWR vendors, reactor models, and fuel bundle designs than for PWR and BWR fuel.) A detailed fuel assembly design and production process are generally still proprietary, and fuel pricing is generally directly negotiated between the nuclear utility owning the PHWR(s) and the fuel fabricator. The design details of the actual fuel fabrication plant are generally also proprietary as are the costs to design, construct, start up, and operate the fabrication facility. For this reason, none of the previous AFC-CBRs has been able to present a PHWR unit fabrication cost based on analysis of LCC data for an actual facility design. Since PHWR-UOX fuel fabrication is a mature and totally privatized FC step, there are no recent, publicly available government estimates such as those that exist for more advanced nuclear facilities where the FOAK (first-of-a-kind) plants are government built and owned. There also have not been any recently completed greenfield PHWR-UOX fuel fabrication plants upon which to address cost-related inquiries to PHWR fuel vendors. There are no PHWR fuel fabrication facilities in the United States, and most new fabrication capacity in the rest of the world has been added on to existing PHWR fuel plants that were built in the 1960s to the 1990s timeframe. Fortunately, the

PHWR-NATU nuclear fuel of today is very similar in design, hardware, and heavy metal composition to that made in the first Canadian fuel fabrication plants built from the 1960s through the 1980s.

Discovery of some old but useful comparative fuel fabrication LCC data. Fortunately, there exists one open-source bottom-up UOX fabrication plant design and cost estimate that was prepared by the United States Atomic Energy Commission government contractor, ORNL (operated by Union Carbide Nuclear Division at the time). The 1978 document ORNL/TM-6501 (Judkins and Olsen 1979a) was prepared as part of the NASAP which investigated dozens of possible FCs in search of those which were inherently proliferation-resistant. This comparative NASAP FC economics effort was described in detail in the Module D1-PR part of this overall AFC-CBR document. ORNL/TM-6501 was the first of a series of documents presenting fabrication facility design and LCC information on multiple fuel types. These reports are also summarized in detail in Module D1-PR. ORNL/TM-6501 is the only fuel fabrication report in the NASAP series based on a true bottom-up estimate where drawings and bills of materials were prepared by a design engineering team followed by the engagement of engineering cost estimators. The important point to be made here is this LWR-UOX fabrication plant is the reference plant from which all other cylindrical fuel types (subject plants) and their designs and LCCs were calculated by the fuel technology transition methodology schematically shown in Figure D1-PR.A.3 of Module D1-PR. Module D1-1 (LWR-UOX) described (1) this plant, (2) the cost estimate made in 1978 for it, (3) how the 1978 cost estimate was modified to reflect today's financial and regulatory environment, and (4) the new resulting unit cost (in 2017 constant USD). This new data was then compared to the literature-based WIT PWR-UOX unit price range in the 2017 AFC-CBR (Dixon et al. 2017) to establish new WIT unit cost data. In this PHWR Module D1-7 report, both the transitional methodology from the bottom-up PWR-UOX design and costs to useful LCC data for a same-throughput size PHWR fuel fabrication facility are described. Before presenting these technoeconomic details, it is useful to consider how the 1978 PHWR LCCs derived by the NASAP reference plant to subject plant transformation methodology are transformed to 2017 USD costs representative of today's economy. The process consists of more than just the application of inflation and incremental escalation considerations. General economic and institutional factors such as interest rates, capital recovery practice, and usefulness of the levelization model to the international nuclear community are important.

The treatment of the engineering economics and calculation of the unit fabrication cost in the 1978 ORNL/TM-6501 and subsequent ORNL-NASAP reports reflects U.S. financial conditions and taxation regulations in effect at that time for a privately owned greenfield plant financed by both the issuance of stock (equity financing) and bonds (debt financing). The revenue requirements model, used to calculate the unit cost, reflected the U.S. Treasury/IRS corporate income tax rates and allowable depreciation/amortization practices used in 1978. Inflation and interest rates were also much higher at that time than they are today. The economic model described later in this section for today's economic conditions is a simpler, non-country specific model based on the international G4-ECONS (Williams and Miller 2007; Williams 2007) modeling methodology used to evaluate advanced Generation IV reactors and their supporting FC facilities. G4-ECONS does not consider taxation, uses only one composite discount rate for borrowing, and assumes recovery of capital over the operating life of the facility. It is not specific to one country's rules or economic policy. Selection of the appropriate discount rate can simulate both private higher-risk equity/debt financing and the lower risks associated with direct government financing or government-guaranteed loans. All these assumptions will be explained in the following sections. Price and its relationship to cost, as well as cost versus capacity scaling, will also be discussed.

D1-7.6.2.3 The ORNL/TM-6501 Report and Subsequent NASAP Reports

The ORNL/TM-6501 report (part of NASAP FC studies referenced as Judkins and Olsen 1979) includes a detailed LCC analysis of a PWR LEU oxide fuel fabrication facility, performed as part of the overall NASAP program from 1978–1980. Additional reports (ORNL 1979a; ORNL 1979b) considering the fabrication cost of alternative, and in some cases more complex fuels such as plutonium-containing MOX and metal alloy fuels, have also been developed within the same program by the same ORNL designers and estimators and use the ORNL/TM-6501 reference PWR-UOX fabrication plant as the starting point of the analysis. The cost of fabricating different—and generally more complex in both material content and manufacturing and HS&E requirements—fuels in subject plants has then been developed as modifications or design transitions made to the detailed, bottom-up PWR-UOX cost estimate in ORNL/TM-6501 (Judkins and Olsen 1979a). This transition methodology was explained in Module D1-PR, "Preface," and Section D1-1.14, "LWR-UOX," of this overall three-module report and in even more detail in the ORNL/TM reports comprising the NASAP fuel fabrication studies.

In the case of the PHWR, we are describing the transition to a simpler fuel design rather than a more complex one, and we encounter a less restrictive plant operating environment than for LWR-UOX fuel. The following factors result in a smaller and less complex facility than for LWR-UOX:

- The PHWR fuel bundles are much shorter and lighter than those for LWRs, hence the tube loading and welding machinery involved are smaller and take up less process building floor space and require less lifting capability such as large cranes
- The tube and bundle inspection equipment needed for QA can be smaller in physical size
- High bay areas for bundle storage are not required—about 12 ft long LWR fuel assemblies are usually stored vertically before shipping.

The above three bulleted items affect mainly the facility capital cost. The following factors affect both capital and operating costs:

- The use of NATU or SEU eliminates or greatly reduces the presence of nuclear criticality as a design factor limiting the throughput of some unit operations
- No front-end UF_6 to UO_2 deconversion step requiring hydrofluoric acid production or use of ammonia is required.

Unlike U mining and U enrichment, PHWR-UOX fuel fabrication is one FC service for which the basic manufacturing technology has changed very little since the early days of CANDU-PHWR commercial nuclear power generation. UOX pelleting/rod insertion/rod bundling technology remains basically the same from the 1960s designs to the present. One process change has been identified; however, even it likely has not affected on the inflation/escalation adjusted total unit fabrication cost by a significant amount. This change is that the automation of some processing and inspection steps has reduced some staff costs; however, other factors, such as regulatory compliance in Canada, material accountability, and greater plant security requirements likely require increased staff.

Description of the basic process chemistry and manufacturing steps for PHWR-UOX fuel fabrication are presented in Section D1-7.5 of this document. A typical NATUO2 powder to finished PHWR-UOX bundle process flowsheet is also included in Figure D1-7.2 and was accessed from ORNL/TM-6640 (Judkins and Olsen 1979b).

In ORNL/TM-6501, a detailed PWR-UOX flowsheet is first developed, and afterwards estimates are provided for the floor space (square footage) necessary for each of the process flowsheet functions or unit operations, plus for support functions including balance of plant. The facility total throughput was assumed at 2 MTHM/day, working 260 days/year in a 24/7 shift system. This results in a downtime-adjusted total annual average throughput of 520 MTHM or 520 MTU/year based on the 71% capacity factor. Based on a colleague’s experience at one of today’s fuel vendors, there are only a few steps in the process that run 24/7. Most of the process runs on only one or two shifts. For this reason, the throughput of an actual plant is based on the production rate of the bottle neck in the process.

The ORNL/TM-6501 design prepared by the engineers in the ORNL Metals and Ceramics Division and the Engineering Division was based on standard design calculations for metallurgical operations, chemical and metallurgical equipment sizing, plant equipment and utility layout in a single-story ventilated building, integration of overhead functions, and preparation of bills of materials specification sheets for final cost estimation. Unfortunately, none of this original late 1970s data was prepared or recorded in electronic form and subsequently archived. The author of this report has been unable to find any original design documentation, and nearly all the individuals intimately involved with this late 1970s effort are retired or no longer living.

All the PWR LCCs from ORNL/TM-6501 are presented in the 2020 Module D1-1 (Uranium-Based Ceramic LWR Fuel Fabrication) part of this report. In later 1979 NASAP documents (Olsen 1979 and Olsen and Judkins 1979), the authors explain how the PWR-UOX was transitioned to a PHWR-UOX plant by (1) using algorithms to scale production equipment to accommodate a shorter bundle and the need for more tubes to fill with pellets and more end welds, (2) recalculate the floor area in a one-story building required for all equipment and operations, and (3) recalculate the materials and consumables, such as zirconium, and the person-hours required to produce the target 520 MTU/yr production. All of this new PHWR fuel fabrication design and operations data was then provided to ORNL cost estimators who re-casted it into the same standard LCC category format as was done for the PWR-UOX facility. All LCCs were calculated in 1978 constant USD. It was the task of the SA&I authors to take this 1978 base constant USD LCC data and convert it to today’s economic/financing environment and 2017 constant USD. The methodology for this 1978 to 2017 transition is described below after the PHWR base costs are presented.

For the presentation of the PHWR-UOX fabrication LCCs below, mostly 2017 USD results will be given; however, for the sake of making useful comparisons between the two-water reactor fuel fabrication technologies, the same data for the baseline or reference PWR-UOX facility based on ORNL/TM-6501 will be shown side-by side for each LCC category.

D1-7.6.3Base Capital Costs

Costs for the main process building construction were estimated parametrically using a USD-per-square-foot formulation for each functional space. Floor space for all the PHWR main process building functions except quality control (QC) were estimated at $1,190/ft^2 (in 2017 USD) which was escalated from $200/ft^2 in 1978 USD. Inflation and escalation assumptions will be explained in another subsection below. The QC area was estimated at $2,380/ft^2 (2017 USD) which was escalated from $400/ft^2 in 1978 USD. The areas or space requirements calculated by the ORNL PHWR-UOX fuel plant designers appear in Table A-6 of ORNL/TM-6640. The $/square foot factors (in 1978 USD) which are applied to these areas appear in Table 8 of the same ORNL document. From this data, a base (before addition of cost-estimating allowances) construction cost of $106.5 million in 2017 USD and $17.9 million in 1978 USD results for a 72,235 ft^2 one-story main process building civil structure. This cost does not include process equipment but does include HVAC (heating, ventilation, and air conditioning). There are other smaller buildings and ancillary site services requirements for the overall civil construction category. These costs, and those for the main process building, are also summarized in Table D1-7.4. The process building floor area required for PHWR-UOX is only 72% of the 100,000 ft$_2$ needed for an equivalent 520

MTU/yr production of PWR-UOX fuel. This reflects the use of smaller and horizontally shorter fabrication equipment for PHWR-UOX production compared to the reference PWR-UOX facility of the same production capacity.

Table D1-7.4. Process building floor areas by unit operation and function for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication plants.

Direct Capital Costs	AREAs		1978$M COSTS		2017$M COSTS	
	Main process Building Civil (red values directly from NASAP documents)					
PROCESS BUILDING LAYOUT AND COSTS BY UNIT OPERATIONS FOR 520 MTU FABRICATION PLANTS	PWR-UOX Area (ft_2) ORNL/TM-6501 Reference Plant	PHWR-UOX Area (ft_2) per ORNL/TM-6522 Subject Plant	PWR-UOX Yr 1978$M from ORNL/TM-6501	PHWR-UOX Yr 1978$M From ORNL/TM 6640	PWR-UOX Building Area Costs in 2017$M	PHWR-UOX Building Area Costs in 2017$M
Conversion or purification to produce UO_2 powder	5,500	2,350	1.100	0.470	8.338	2.797
UO2 powder milling, blending, and storage	4,700	2,350	0.840	0.470	7.125	2.797
Subtotal: conversion to pelleting-ready packaged powder	10,200	4,700	2.040	0.840	15.463	5.593
UO_2 powder loading and pelleting	1,900	1,900	0.380	0.380	2.880	2.261
UO_2 pellet sintering, grinding, and inspection	5,850	5,850	1.170	1.170	8.869	6.962
Subtotal: pellet production operations	7,750	7,750	1.550	1.550	11.749	9.223
Fuel rod loading and welding	2,780	2,515	0.556	0.503	4.214	2.993
Fuel rod inspection and storage	7,000	7,740	1.400	1.548	10.612	9.211
Subtotal: rod loading operations	9,780	10,255	1.956	2.051	14.826	12.203
Fuel assembly fabrication	3,000	6,925	0.600	1.385	4.548	8.241
Fuel assembly weighing, cleaning, and inspection	3,400	2,040	0.680	0.408	5.154	2.428
Fuel assembly packaging and shipping	4,000	2,000	0.800	0.400	6.064	2.380
Subtotal: fuel assy operations	10,400	10,965	2.080	2.193	15.766	13.048
Scrap recovery and aqueous waste processing	2,000	1,500	0.400	0.300	3.032	1.785
Subtotal Areas (ft2) & costs ($M) for main unit operations above	40,130	35,170	$8.026	$7.034	$60.837	$41.852

Direct Capital Costs	AREAs		1978$M COSTS		2017$M COSTS	
	Main process Building Civil (red values directly from NASAP documents)					
PROCESS BUILDING LAYOUT AND COSTS BY UNIT OPERATIONS FOR 520 MTU FABRICATION PLANTS	PWR-UOX Area (ft$_2$) ORNL/TM-6501 Reference Plant	PHWR-UOX Area (ft$_2$) per ORNL/TM-6522 Subject Plant	PWR-UOX Yr 1978$M from ORNL/TM-6501	PHWR-UOX Yr 1978$M From ORNL/TM 6640	PWR-UOX Building Area Costs in 2017$M	PHWR-UOX Building Area Costs in 2017$M
Operational support area including fuel assembly hardware fabrication	20,065	6690	4.013	1.338	30.419	7.961
(Most zirconium parts such as tubes are fabricated from nuclear-grade zirconium metal. Metal costs are in recurring costs appearing in a later table.)						
Stores	2,000	2,000	0.400	0.400	3.032	2.380
Facility support area	9,135	7,440	1.827	1.488	13.849	8.854
Change rooms for contaminated areas	2,005	1,415	0.401	0.283	3.040	1.684
QC laboratories	7,000	3,500	2.800	1.400	21.224	8.330
Maintenance Area	19,665	16,020	3.933	3.204	29.812	19.064
Subtotal ancillary floor space	39,805	30,375	9.361	6.775	70.956	40.311
Total in ft$_2$ (col C) or $M (cols F, H, J)	100,000	72,235	$21.400	$15.147	$162.212	$90.125
			PWR-UOX	PHWR-UOX		
DIRECT CAPITAL COST FOR ALL STRUCTURES AND ASSOCIATED HVAC, SECURITY, & ES&H EQUIPMENT	–	–	1978$M CIVIL FOR PWR-UOX	1978$M CIVIL FOR PHWR-UOX	PWR-UOX 2017$M CIVIL	PHWR-UOX 2017$M CIVIL
Process building costs (from above)	–	–	21.400	15.147	162.212	90.125
Land purchase	–	–	0.500	0.500	2.975	2.975
Site preparation	–	–	0.500	0.500	2.975	2.975
Licensing and environmental	–	–	0.400	0.400	2.38	4.165
Security System	–	–	0.300	0.300	1.785	0
Office Building	–	–	1.500	1.057	8.925	6.289
Subtotal before contingency and indirects	–	–	$24.600	$17.904	$181.252	$106.529
Effective inflation + escalation multiplier from 1978$ to 2017$ for all PHWR direct costs is calculated as >>	–	5.95	–	–	–	–

In the United States, such process buildings handling natural or enriched U of U-235 assay 10% or less would be categorized as USNRC Category-III facilities from the standpoint of safeguards and security. This is the least prescriptive of the three Categories (I, II, & III) defined in USNRC 10 CFR 70 regulations for FC facilities. From a proliferation or diversion "nuclear materials attractiveness" standpoint, a PHWR plant using NATU oxide (UO_2) feed is extremely low risk and is lower risk than for a PHWR-UOX facility using 2 to 5% U-235 $LEUF_6$ feedstock. Attractiveness level comment: if a proliferator wishes to produce a given amount of weapons-grade highly enriched U (HEU), feeding an enrichment plant with typical LWR LEU assay feed 2.5 to 5% U-235 requires far less separative work units (SWUs) than the SWU requirements for feeding an enrichment plant with NATU (0.7% U-235).

It should be noted that the civil structure-related costs were one area where parametric ($\$/ft^2$) rather than straight-up bricks and mortar-type bottom-up cost estimating was used by the ORNL cost estimators. (Table 8 of ORNL/TM-6640 lists the $\$/ft^2$ factors applied to each of the PHWR-UOX process areas, and Table A-7 of the same document presents the corresponding costs in 1978 USD.) Experience-based engineering estimating manuals with $\$/ft^2$ values for different building construction types have existed for over 75 years and still are used today for both residential and industrial construction cost estimating (Doheny 2021).

Parametric and some bottom-up estimations were used by ORNL designers and cost estimators in 1978 to estimate the process equipment design requirements and the associated costs for the major flowsheet functions. Similar estimating techniques were used for balance-of-plant and overhead functions such as stores, QC labs, change rooms, etc. For a non-LWR fuel type, the equipment list by major plant unit operations areas and associated costs was not provided in the ORNL reports. Such data were provided only for the LWR-UOX reference fuel fabrication facility. The major cost category totals for each subject plant fuel type are provided in ORNL/TM-6640 (Judkins and Olsen 1979b) in 1978 USD and for the PHWR-UOX facility in the first column of Table A-8 of that document.

A total base equipment capital cost of $163.6 million in 2017 USD ($27.5 million in 1978 USD) results. No indirect costs other than engineering were called out. This PHWR-UOX facility, as well as all the subject fuel fabrication plants in the NASAP study, are considered Nth-of-a-kind (NOAK) facilities. The following Table D1-7.5 totals the base capital costs for the whole PHWR-UOX facility (i.e., the capital cost before the addition of indirect, contingency, owner, and financing costs). These adders will be discussed in a section below since they were treated differently for some allowances by the 1978 ORNL and 2021 SA&I estimating teams.

Table D1-7.5. Comparative base capital cost totals for 520 MTU/yr PWR-UOX and PHWR fuel fabrication facilities.

	PWR-UOX 1978$M	PWR-UOX 2017$M	PHWR-UOX 1978$M	PHWR-UOX 2017$M
Base Civil (Buildings Incl. HVAC)	24.1	186.9*	17.9	106.5
Base Installed Equipment	34.2	203.5	27.5	163.6
Base Total Capital	58.3	390.4	45.4	270.1

*For less robust process building per ORNL/TM-6501, more robust building would be $181.3 million.

These civil costs are for a standard industrial type building. As will be discussed below, an additional cost was added by SA&I to the ORNL-NASAP estimate for the PWR-UOX process building to cover use of reinforced concrete walls and ceiling to provide additional robustness for physical protection of $LEUO_2$. This construction upgrade was deemed not necessary for the PHWR facility because of its use of natural rather than enriched U.

D1-7.7. BASE RECURRING OPERATIONS AND MAINTENANCE COSTS

Significant labor and material costs exist for fabrication of nuclear fuel. The ORNL/TM-6501 estimators first prepared an organizational chart and staff count for the overall PWR-UOX plant operations. The number of personnel required to staff a three-shift operation was calculated for each major process step. The total PWR-UOX reference plant staff count was around 720 full-time equivalents (FTEs), and the average fully loaded salary (including all overheads, benefits, and taxes) was calculated as ~$18,000/FTE in 1978 USD, which would be $67,500/FTE in 2017 USD. To convert the PWR-UOX staffing cost estimate to one for a PHWR-UOX facility, the ORNL estimators considered the complexity of operations and the operating environment vis-à-vis the same sized PWR-UOX facility. Details of these calculations, such as time and motions studies, are not available nor are they archived; however, the rolled-up results are presented in Table A-9 of ORNL/TM-6640 in 1978 USD and as part of Table D1-7.6 below in both 1978 USD and 2017 USD.

Materials and consumables costs, including utilities, are also recurring costs and include specialty gases, chemicals, tools, fuels (such as natural gas for sintering furnaces), personnel safety equipment, solvents, and most significantly the mostly reactor-grade zirconium or zirconium alloy metal required for manufacturing the hardware enclosing the UOX pellets and forming a structurally sound fuel assembly or bundle. In ORNL/TM-6501 (for PWR-UOX) and ORNL/TM-6640 (for some other fuel types including PHWR-UOX), it was assumed that all zirconium hardware was manufactured in-house, and that most the remaining fuel fabrication facility space consisted of sintering, rod loading, rod end cap welding, rod inspection, and loading of the rods into spacers and other structural hardware. Some U.S. LWR fuel fabricators such as GE-Hitachi in Wilmington, NC perform zirconium hardware manufacture on site; others such as Westinghouse purchase fabricated zirconium parts from an offsite, non-nuclear facility. This is also true for PHWR-UOX CANDU fuel in Canada, where Cameco Fuel Manufacturing in Port Hope, Ontario has a nearby facility for zirconium parts fabrication.

For ORNL/TM-6501 (PWR-UOX), the ORNL estimators contacted hardware vendors to verify the costs for zirconium parts. The costs of other supplies, utilities, and consumables were estimated from requirements dictated by the number of personnel, the equipment throughputs and energy requirements for the various operations, and the desired 520 MTU/yr production rate. For the 1978 PHWR-UOX fuel fabrication plant, the ORNL estimators utilized scaling calculations and PHWR-UOX fuel design data to calculate the materials and consumables annual requirements and annual costs. Again, no detailed 1978 ORNL reference PWR-UOX to subject PHWR-UOX scaling calculations or computer algorithms are available in reports or archives. A summary of these PHWR-UOX recurring costs for materials appears in Table A-19 of ORNL/TM-6640 (Judkins and Olsen 1979b) in 1978 USD and in the Table D1-7.6 in both 1978 USD and 2017 USD.

Table D1-7.6. Comparison of annual recurring operations and maintenance (O&M) and equipment replacement costs for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication plants.

Recurring LCC Category	PWR-UOX 1978$ Annual Cost in $M/yr From ORNL/TM-6501	PHWR-UOX 1978$ Annual Cost in $M/yr From ORNL/TM-6522	Composite Inflation & Incremental Escalation Multiplier Used for both PWR-UOX and PHWR-UOX	PWR-UOX 2017$ Annual Cost in $M/yr	PHWR-UOX 2017$ Annual Cost in $M/yr
PERSONNEL (All costs include 33% burden)					
Direct manufacturing and Maintenance labor	9.35	6.56	3.75	35.04	24.60
Non-manufacturing personnel including labor supervision, management, and general and administrative costs	3.80	2.72	3.75	14.25	10.20
Subtotal personnel-related costs	13.14	9.28	3.75	49.29	34.80
CONSUMABLES					
Direct & indirect materials, supplies	2.14	1.75	3.75	8.03	6.56
Hardware feedstock (mostly nuclear-grade zirconium metal feedstock forms)	20.90	9.06	3.75	78.37	33.98
Utilities (water, sewer, natural gas, electricity)	0.24	0.18	3.75	0.90	0.68
Subtotal consumables	23.28	10.99	–	87.30	41.21
Total recurring annual O&M costs	36.42	20.27	–	136.59	76.01
Annualization of process equipment capital replacement costs	1.71	1.38	5.95	10.17	8.18
TOTAL RECURRING COSTS in $M/yr	38.13	21.65	3.85*	146.76	84.109

All process equipment assumed to be replaced every 20 years; hence $34.2M/20yr in 1978$.

* Effective average inflation and escalation multiplier

D1-7.8. RESULTS OF ECONOMIC ANALYSIS UTILIZED IN 1978 BY ORNL-NASAP ANALYSTS TO DETERMINE UNIT PRICE OF PWR AND PHWR UOX

In 1978, the ORNL analysts utilized a set of cost levelization algorithms based on a plant operating life and capital recovery period of 20 years and standard U.S. financing, amortization, and depreciation methodology at the time. Using the 1978 USD base capital and recurring LCCs above and a set of FORTRAN-based algorithms, they calculated a levelized unit cost for each fuel type under three financing risk scenarios with each assuming 20 years of plant operations. This unit cost essentially represents a price, since under balanced market conditions, the calculated unit cost covers all ROI. The following Table D1-7.7, which extracts published unit fabrication cost results from ORNL/TM-6522, shows the 1978 USD ORNL-NASAP-calculated unit costs for both PWR-UOX and PHWR-UOX under the three financing risk conditions:

Table D1-7.7. ORNL-NASAP calculated 1978 USD unit costs for 520 MTU/yr PWR-UOX and PHWR-UOX contact-handling fuel fabrication plants with 20-year lives.

(Plant Lifetime for Capital Recovery and Operations is 20 years)	Low-risk Government Financing under 1978 Economic Conditions	Medium-risk Typical Industrial Financing under 1978 Economic Conditions	High-risk Industrial Financing under 1978 Economic Conditions
PWR-UOX Unit Cost in 1978$ per kg U >> (Reference Plant)	100	130	150
PHWR-UOX Unit Cost in 2017$ per kg U >> (Subject Plant)	60	80	95

Comparative 1978 data from the ORNL-NASAP studies is interesting and useful; however, the existing need is for data that represents early 21st century economic conditions and a more generic international approach to LCC levelization/annualization algorithms and the calculation of the unit fabrication costs for NOAK facilities. The following sections describe the three important aspects of transitioning the 1978 ORNL-NASAP base LCC data to 2017 conditions: (1) derivation and use of 1978 USD to 2017 USD cost multiplication factors that include general inflation and any incremental escalation above general inflation endemic to nuclear projects, (2) use of internationally recognized methodology and the associated algorithms for converting base LCCs to a single levelized unit fabrication cost representative over a longer plant operating life, and (3) inclusion of end-of-life (EOL) decontamination and decommissioning costs.

D1-7.9. ECONOMIC ANALYSIS UTILIZED FROM 2018–2021 BY SA&I TO DETERMINE THE WHAT-IT-TAKES UNIT COST OF PWR AND PHWR UOX IN 2017 USD

To transition the 1978 ORNL LCC estimate to 2017 conditions, one must consider the following factors:

- General inflation and industry-specific escalation incremental to the inflation rate
- Other economic factors such as interest rates and taxation
- Regulatory changes affecting project LCCs
- Process technology and design changes affecting cost.

General Inflation and Industry-Specific Escalation Incremental to the Inflation Rate. General inflation, as measured by the implicit price deflator (IPD) and cost-of-living aka consumer price index (CPI) in the United States, has caused the average market basket price (weighted average of prices for various commodities and services as defined for each measure) to increase from 1978 to 2017 by factors of 2.95 (IPD) and 3.75 (CPI), respectively. Incremental escalation would be the additional average annual increase in prices pertinent to the industry of interest above this general inflation rate. Unfortunately, for nuclear reactor construction in the United States, this escalation above inflation has been above 3%/year for those years (1970s and 1980s) in which significant nuclear construction was underway. The question is whether this nuclear project escalation above general inflation is also partially or fully applicable to nuclear FC facilities such as fuel fabrication plants?

Other Economic Factors Such as Interest Rates and Taxation. The discounted cash flow analysis used to calculate the levelized PWR-UOX unit cost and unit costs for other fuel types assumed the economic conditions present at the time (1978). The 1970s were a time of high inflation, hence, very high interest rates were experienced for companies and individuals borrowing money. The 1970s were also a time of higher borrowing rates for the U.S. government, as measured by the Federal Reserve discount rate. Corporate U.S. federal income tax brackets were also much higher than today’s and were around 46% in 1978. Local property taxes were also likely higher in 1978, since many of the local tax incentives to locate higher-wage type industries, such as nuclear ones in a particular location, did not exist back then.

The question is now how to consider these four factors into the calculation of a levelized 2017-unit cost for PWR-UOX fuel assemblies and PHWR-UOX fuel bundles from a new, NOAK greenfield fuel fabrication plant.

Inflation/Escalation. It was recognized that the 3% escalation (above inflation) experienced by U.S.-built nuclear reactor construction costs during the late 1970s and most of the 1980s does not necessarily apply to nuclear FC facilities such as fuel fabrication plants. There is, however, a very real cost risk factor associated with all nuclear projects as a result of multiple factors including: changing regulation, ES&H litigation, shortages of nuclear-qualified craft workers, supply chain issues, and the tendency of nuclear project managers to be optimistic on project cost and schedule estimates made at project inception. It was decided that for fuel fabrication capital costs a nuclear risk-informed, combined inflation, and incremental escalation factor (2017 USD cost divided by 1978 USD cost) based on recognized industry and government indices was required. Chapter 8 of the 2017 AFC-CBR (Dixon, et al.) includes a discussion of such a calculated factor, its data sources, and a Table 8.3 listing the factor (a multiplier) for years 1965 through 2017. Other LCCs, such as recurring annual personnel and utility costs, involve less risk, and the application of a government-published, CPI-only based factor can be used. Table D1-7.8 below shows the composite factors (i.e., multipliers) used to convert the 1978 USD LCCs by category in the ORNL/TM documents from 1978 USD to 2017 USD. The table also includes the multiplier definitions and rationale for use.

Process Changes and Regulatory-Mandated Design Changes. The UOX fuel fabrication processes themselves for both PWR-UOX and PHWR-UOX have changed little from 1978 and involve mostly standard chemical process and metallurgical equipment, much of which can be ordered off-the-shelf without serious supply chain issues. (Note, however, that in most cases the fuel fabrication process must be qualified by a national regulator, such as the USNRC, and that QA certification for all equipment items and operations is essential.) In the case of the PWR-UOX facility, the one major change that was identified for today’s U.S. regulatory environment was including the cost of a considerably more robust process building for LWR EUO_2 than that required by U.S. nuclear FC regulations in 1978. The rationale for this change was discussed in Module D1-1. For the PHWR-UOX process building, which houses only NATU and does not require hydrogen fluoride handling, it was assessed that no additional physical structure robustness, such as the use of reinforced concrete for all walls and ceiling, was necessary. The HVAC system would still have to accommodate current requirements for airborne radionuclide particles (UOX dust), normal industrial dusts, and radon. The ORNL-NASAP designers had already considered

HVAC as part of the main process building civil cost. Scrap recycle will also require some aqueous operations which must consider regulations for low level liquid waste.

Table D1-7.8. Multiplication factors used to convert 1978 USD to 2017 USD for various life cycle categories for the PHWR-UOX fuel fabrication facility.

Composite inflation-escalation factor (2017 cost/1978 cost): a multiplier	Indices utilized for multiplication factor calculation and rationale for use	LCC categories for which it is applied
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, DOE Nuclear Construction, PCCI, and IPD.	Capital cost of main process and auxiliary buildings, process equipment, environmental support, security systems costs, preoperational costs, and replacement equipment
3.75	CPI from 1978 to 2017. Since this factor is applied to mostly personnel-related, annual recurring costs, it was felt that the consumer item "market basket" essentially covered by worker salaries would be more appropriate than the more generic 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 costs, purchased material costs, utility costs

Applying to both the base building and the base equipment costs a contingency allowance of 10%, and an indirect cost allowance of 20% of total direct costs as typical for chemical plants (Peters and Timmerhaus 2003), would yield a total PHWR construction cost of $334 million in 2017 USD. Table D1-7.9 below shows a breakdown for the various components of the capital cost.

It should be noted that the base capital costs in Table D1-7.5 are for a USNRC Category-III contact-handling facility with hoods and fans being the predominant methods of personnel protection from airborne radionuclides. No gloveboxes or hot cells are required. For the PWR-UOX plant, the EUF_6 to EUO_2 conversion area where hydrofluoric acid (HF) is handled must have its own special containment and ventilation requirements.

The recurring, annualized O&M costs (Table D1-7.6) from the 1978 ORNL/TM-6501 and ORNL/TM-6640 are assumed to only undergo general inflation from 1978 to 2017. It is likely that more security personnel would now be required; however, any increase in this staffing cost category should be more than offset by automation in the fabrication process area and the need for fewer chemical and metallurgical operators. Note in Table D1-7.6 that capital equipment replacements are averaged over the plant life for purposes of cost levelization (aka annualization). It is assumed that on the average all $27.5 million (1978 USD) worth of equipment is replaced every 20 years.

The PHWR facility annual O&M, including personnel, administration and overhead, materials (including all the zirconium metal for fuel assembly hardware but excluding the NATU dioxide [UO_2] feed itself), plus all the chemicals used in the fabrication process, and the utilities, are $20.3 million in 1978 USD, or $76 million in 2017 USD. The cost of the natural UO_2 feed material has inherent U ore [U_3O_8] and at-the-mill purification steps which are combined under a separate mining and milling unit cost covered in Module A1 of the AFC-CBR.

Cost Levelization Methodology Applied by SA&I to Adjusted LCCs. The remainder of this section deals with conversion of the adjusted 2017 USD base LCCs to a unit cost (price) for the PHWR fuel fabrication service. It was decided to use a less country specific, more universal, and simpler levelized unit cost calculation technique than the business model approach used in ORNL/TM-6501 (Judkins and Olsen 1979a) and ORNL/TM-6522 (Olsen, Judkins, Carter, and Delene 1979). Fortunately, a well-documental methodology exists in the G4-ECONS methodology (Williams and Miller 2007; Williams 2007) developed for calculating the levelized unit electricity cost from LCC data for nuclear power plants. When this EXCEL-based tool was developed from 2004 to 2007 an adjunct program called G4-ECONS-FC was also developed specifically for converting LCC data on FC facilities into a levelized unit cost of product or service over the entire operating life of the plant. To make this PHWR-UOX fuel fabrication analysis more comparable to other DOE-NE SA&I FC cost studies the following changes and assumptions have been made:

- **Plant Lifetime.** The full operations lifetime of the fuel fabrication facility has been extended from 20 years (as per ORNL/TM-6522) to 50 years—as per current SA&I practice. Uniform O&M costs will be assumed for 50 years, and a uniform annualized capital recovery will be calculated over the same 50 years, i.e., the operating lifetime of the plant. It should be noted that the ORNL 1978 20-year plant might be operated for more than 20 years with only recurring costs incurred from year 21 onward. Use of a short amortization or write-off period for up-front capital costs is common in Western economies but does not allow the calculation of a levelized cost over the entire operating life of the facility. The levelized unit cost over the plant operating life is a much better figure-of-merit for comparing the cost effects of various technology alternatives.
- **Allowances.** Good cost-estimating practice requires adjustment of base direct capital costs with the addition of indirect costs and contingency. The PWR-UOX plant described in ORNL/TM-6501 either did not explicitly include these or they were buried on other cost categories. A subsequent NASAP report, ORNL/TM-6522, suggested adding 10% of the direct civil construction costs to cover contingency and 20% of the resulting sum to cover indirect costs. Based the Generation IV Cost Estimating Guidelines (Williams and Miller 2007) it was decided that these allowances should also apply to equipment costs, especially since installation and pre-installation testing often has associated schedule and manpower cost uncertainties. Table D1-7.9 shows the addition of contingency and indirect cost allowances. The table also shows the addition of a preoperational cost allowance, also used in most of the 1978 ORNL/NASAP reports such as ORNL/TM-6522. It is calculated by taking 152% of a typical operating year's projected non-material recurring O&M costs. Preoperational costs are an Owner's Cost covering mostly start-up activities and are included as part of the total capital cost. Note that PWR-UOX costs are also included the table below for purpose of comparing the two-water reactor UOX fuel types.

Table D1-7.9. Capital costs with allowances (in both 1978$M and 2017$M for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication facilities).

LCC Category	PWR-UOX Civil 1978$M Capital Costs	PWR-UOX Eqt. 1978$M Capital Costs	PWR-UOX Total 1978$M Capital Cost	PHWR-UOX Civil 1978$M Capital Costs	PHWR-UOX Eqt. 1978$M Capital Costs	PHWR-UOX Total 1978$M Capital Costs
Direct capital costs without allowances (Base costs)	24.6	34.2	58.8	17.9	27.4	45.3
10% contingency on direct costs	2.5	3.4	5.9	1.8	2.7	4.5
20% indirect cost allowance on (direct costs + contingency)	5.4	7.5	12.9	3.9	6.0	10.0
Subtotal overnight cost for civil plus equipment	**32.5**	**45.1**	**77.6**	**23.6**	**36.2**	**59.8**
Other front-end costs treated as capital						

LCC Category	PWR-UOX Civil 1978$M Capital Costs	PWR-UOX Eqt. 1978$M Capital Costs	PWR-UOX Total 1978$M Capital Cost	PHWR-UOX Civil 1978$M Capital Costs	PHWR-UOX Eqt. 1978$M Capital Costs	PHWR-UOX Total 1978$M Capital Costs
Preoperational costs: (152% of one-year of 1978$ non-material recurring O&M costs) [essentially an owner's cost to cover start-up activities]	–		20.3	–		14.4
Total overnight capital cost in 1978$M	–		98	–		74
LCC Category	PWR-UOX Civil 2017$M Capital Costs	PWR-UOX Eqt 2017$M Capital Costs	PWR-UOX Total 2017 $M Capital Cost	PHWR-UOX Civil 2017$M Capital Costs	PHWR-UOX Eqt 2017$M Capital Costs	PHWR-UOX Total 2017 $M Capital Cost
Direct capital costs without allowances (base costs)	181.3	203.5	384.8	106.5	163.6	270.1
10% contingency on direct costs	18.1	20.3	38.5	10.7	16.4	27.0
20% indirect cost allowance on (Direct costs + Contingency)	39.9	44.8	84.7	23.4	36.0	59.4
Subtotal overnight cost for civil plus equipment	**239.3**	**268.6**	**507.9**	**140.6**	**216.0**	**356.6**
Other front-end costs treated as capital						
Preoperational costs: (152% of one-year 1978$ non-material recurring O&M costs) × (inflation & incr. escalation multiplier of 5.95 for a higher risk like cycle start-up activity) [essentially an owner's cost to cover start-up activities]	–		121.0	–		85.6
Total overnight capital cost in 2017$M	–		**629**	**–**		**442**

- **Construction Financing Costs.** It is assumed that the funds required to construct the PHWR fuel fabrication plant will need to be borrowed, and an interest during construction (IDC) (i.e., financing, amount needs to be calculated for the 5 years of design and construction activities). Continuous discounting at a real discount rate of 3% is used for the IDC calculation, and an S-curve shaped spending pattern is assumed for the cumulative design/construction cost. Table D1-7.10 shows the inputs and results of the IDC calculation. The lump sum IDC calculated is added to the overnight capital cost to obtain the total financing-inclusive capital cost (TCC or TEC). Note if this IDC, also known as construction financing cost, is not included, the capital cost total is called the overnight cost (i.e., the cost if the facility could be constructed overnight with no financing interest costs incurred). PWR-UOX results are also shown for comparison purposes.

Table D1-7.10. Total capital cost including interest during construction for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication facilities (2017 USD).

IDC Calculation (Construction Financing Costs)		
	PWR-UOX	PHWR-UOX
Years required to design, procure equipment, construct, and start up fabrication facility	5	5
Real discount rate for construction financing	3%	3%
Calculated lump sum IDC (interest during construction) as percentage of overnight cost	7.73%	7.73%
(Cumulative up-front spending is in the shape of an S-curve)		
Fabrication plant overnight capital cost ($M)	629.1	420.2
Calculated IDC ($M)	48.6	32.5
Total Capitalized Cost to be recovered ($M)	677.7	452.7

- **Recovery of Capital Costs.** The PHWR fabrication facility is assumed to be a NOAK plant since the process technology is mature. The 3% real discount rate is used for calculation of the IDC is also used for amortization (capital recovery) of the financing-inclusive TEC over the assumed 50-year plant life. This real discount rate free of general inflation reflects the lower risk associated with a NOAK facility and the fact that PHWR fuel fabrication is a relatively non-hazardous activity compared to other FC steps, such as reprocessing or spent fuel handling, and the nuclear reactors themselves. At the time of plant commissioning (commercial operations) the sum of the overnight capital cost plus the IDC (financing) is rolled over into a 50 year mortgage of equal annual payments in much the same way as a conventional real estate entity would be mortgaged in the United States. The annual payment (divided by the average annual production) represents the capital recovery component of the levelized unit cost. The Generation IV Cost Estimating Guidelines (Williams and Miller 2007) and the G4-ECONS User's Manual (Williams 2007) present the formula, repeated below, used for the amortization calculation. Table D1-7.11 shows the inputs and outputs to the capital recovery algorithms. The following is the formula for the capital recovery factor (CRF) or fixed charge rate,

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (1)$$

where

i = the real discount rate

N = the number of years over which the capital is recovered.

This CRF when multiplied by the financing-inclusive TCC, gives the amount which must be paid over every year of the facility's operating life to recover the front-end costs. Essentially this is the annual mortgage payment which amortizes all front-end costs (TCC). Table D1-7.11 also shows the same data for the PWR-UOX fabrication facility.

Table D1-7.11. Inputs and outputs to the annualized capital recovery calculation for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication facilities.

Capital Recover Factor for Levelization (Amortization) of Financing-inclusive Capital Costs		
Fabrication Plant Fuel Type	PWR-UOX	PHWR-UOX
Real (inflation free) interest or discount rate for recovery of capital	3.0%	3.0%
Years to amortize TCC = operating life of facility (yrs)	50	50
Payments per year into fund	1	1

Capital Recover Factor for Levelization (Amortization) of Financing-inclusive Capital Costs		
Fabrication plant total capital cost (TCC) total (including all allowances and financing) ($M)	677.7	677.7
Capital recovery factor (CRF aka fixed charge rate)	0.03887	0.03887
Annual payment required for capital recovery ($M/yr)	26.34	17.59

- **Average Annualized Production.** Production of PHWR fuel assemblies at a reference uniform rate of 520 MTHM/yr (or 520 MTU/yr) is assumed over all 50 years of plant operations. The fuel fabrication plant capacity factor of ~71% is already rolled into this average annual production rate. Over its life the plant will process 26,000 MTU which represents over 1.3 million PHWR fuel assemblies of ~20 kgU each. In 1978, this production rate would have provided fuel reloads for four to five 1,000 MWe PHWR nuclear power plants. (Note that actual fuel fabrication facilities might operate for more than 50 years if their licenses are renewed, and 50 years of operations has been chosen for all FC facilities in the overall AFC-CBR project.)
- **End-of-Life Costs.** After 50 years of operations, the plant is assumed to be decommissioned to the point where all radioactively contaminated material and equipment have been removed and dispositioned, and a clean building and site can be made available for other purposes. A lump decommissioning sum is calculated using a decontamination and decommissioning (D&D) rule-of-thumb for chemical plants that estimates approximately 10% of the direct capital costs will cover D&D. A decommissioning fund or escrow account is created to collect a set amount annually over all 50 years of operations so that the lump sum D&D amount is available at EOL. It is assumed that the D&D fund earns 1.5% per annum, since a long-term sinking fund or escrow fund generally earns less than that associated with a mortgage type interest rate. The formula used for calculation of the annual fund contribution is also discussed in the G4-ECONS documentation and the Gen IV Cost Estimating Guidelines. Table D1-7.12 below shows the inputs and outputs to the algorithm calculating the annual contribution to the D&D fund. The following is the sinking fund factor formula used in the algorithm which calculates the factor in the second to last line of Table D1-7.12,

$$SFF(i,N) = \frac{i}{(1+i)^{N}-1} \qquad (2)$$

where

i = interest rate assumed available for the D&D escrow fund

N = the number of years over which it is collected.

Table D1-7.12. Inputs and outputs to D&D calculation for 520 MTU/yr PWR-UOX and PHWR-UOX fuel fabrication facilities.

Decontamination & Decommissioning (D&D) Fund Calculation in 2017 USD		
Fabrication Plant Fuel Type	PWR-OUX	PHWR-OUX
Real (inflation free) interest rate for D&D sinking (aka escrow fund)	1.5%	1.5%
Years to accumulate fund = operating life of facility (yrs)	50	50
Payments per year into fund	1	1
Fabrication plant capital cost total (not incl contingency and indirect costs) ($M)	384.8	270.1
Percent of direct capital cost total used to approximate lump sum D&D cost	10%	10%
Lump sum D&D cost needed at EOL ($M)	38.5	27.0
Sinking fund factor	0.01357	0.01357
Annual payment required for D&D sinking fund ($M/yr)	0.522	0.367

Again, PWR-UOX plant D&D cost data are shown for purposes of comparison. D&D costs for both PWR and PHWR facilities are highly uncertain due regulatory uncertainty. The 10% of direct capital rule-of-thumb is often used for D&D of non-reactor FC facilities. In the levelized unit cost, D&D costs are nearly washed-out by the effects of discounting over many decades of operation.

Unit Cost Summary. The three levelized and annualized cost amounts (capital recovery, recurring costs, and D&D) can now be converted to units costs in $/kgHM or $/kgU by dividing each by the annual baseline production rate of 520,000 kgU/yr. Note that in FC calculations, it is customary to deal with elemental heavy metal for material balance calculations, hence the need for the $/kg U rather than the $/kg UO_2 figure-of-merit. Table D1-7.13 shows the breakdown of the annualized and unit costs by major aggregated LCC category and the percent contribution of each.

Table D1-7.13. Summary of levelized costs in 2017$M/year and 2017$/kgU for components of PWR-UOX and PHWR-UOX fuel fabrication facilities.

UOX FUEL FABRICATION (50 Yr Plants)	2017 Constant $ PWR-UOX Production Rate of 520 MTU/yr			2017 Constant $ for PHWR-UOX Production Rate of 520 MTU/yr		
SUMMARY of ANNUAL and UNIT COSTS at Capital Recovery and IDC Discount Rate of 3.00%	$M/yr	$/kgU	Percent Contribution to Total	$M/yr	$/kgU	Percent Contr to Total
Capital Recovery	26.34	50.65	15.2%	17.59	33.84	17.2%
Recurring Costs Incl. O&M	146.76	282.24	84.5%	84.19	161.91	82.4%
D&D Sinking Fund at 1.5% Interest Rate	0.52	1.00	0.3%	0.37	0.71	0.4%
Totals	173.63	333.9	100.0%	102.15	196.5	100.0%

This total PHWR fuel fabrication unit cost value of 196.5 $/kgHM (or $/kgU) compares well with the range values derived in the Cost Basis Report (CBR 2017) for the fabrication of PHWR-CANDU-NATU-oxide fuel, with a low, mode (most likely), high, and mean of respectively 125 $/kgHM, 218 $/kgHM, 327 $/kgHM, and 224 $/kgHM. This unit cost can be interpreted as a unit price in the sense that if all fuel production could be sold at this value as revenue, all LCCs, including returns to investors, would be covered. It can also be seen on a percent contribution to the unit cost basis that recurring O&M costs greatly exceed capital amortization of the facility. This is not surprising, since fuel fabrication is a value-added service with considerable labor-hours and additional costly materials such as nuclear-grade zirconium which are introduced into the plant.

It is of interest to consider what unit costs for this 50-year PHWR-UOX facility would result if the 1978 base capital and base recurring costs from ORNL/TM-6501 were inserted into the SA&I G4-ECONS based model with 2017 financing assumptions. A unit cost of $48/kgU was the result and is low compared to the $60 to 95/kgU unit cost values obtained by the ORNL authors. This makes sense, however, in light of the fact the 1978 discount rates would have been much higher, and a much shorter 20-year life was assumed. Operating a plant for only 20 years instead of 50 means that more front-end fixed capital costs are distributed into the total unit cost, thus requiring a much higher capital recovery contribution to the overall levelized unit cost.

The ratio of the 2017 USD unit cost to the 1978 USD unit cost is 4.1 (i.e., 196/48). This increase is due to general inflation and nuclear risk-related incremental escalation.

Unit Cost/Plant Capacity Scaling. It is useful to consider how the unit cost might scale with the plant production capacity, especially since today's PHWR fuel fabrication facilities are tending toward larger plants more in the 1,000 to 1,500 MTU range as opposed to the NASAP/ORNL reference size of

520 MTU/yr (nominally 2 MTU/day). ORNL/TM-6522 did consider cost scaling by the inclusion of cost scaling exponents derived for scaling equations of the form.

$$C/C_{ref} = (P/P_{ref})^x \qquad (3)$$

where

C = a cost of a non-reference size LCC

C_{ref} = the cost of that item for the reference size or baseline plant

P = the non-reference size production rate

P_{ref} = the reference plant size production rate

X = the scaling exponent for the LCC category of interest

(for example, O&M, capital equipment and civil capital).

Table D1-7.14 shows the values that the 1978 ORNL/NASAP authors assigned the scaling exponent x for various LCC categories applicable to different types of fuel fabrication plants and their radionuclide containment characteristics required for fuel handling. A few categories, such as D&D, did not appear in the NASAP reports, so the SA&I author of this report selected the ones in the table below. Classic chemical engineering economics textbooks such as *Plant Design and Economics for Chemical Engineers* (Peters and Timmerhaus 2003) were used by ORNL and SA&I for the selection of appropriate scaling factors. Multiple cost/scaling equations and exponents are tabulated in this *McGraw-Hill Chemical Engineering Series* text for dozens of equipment and process plant types.

Table D1-7.14. Exponential scaling factors used inI fuel fabrication facility economic studies.

Scaling Factor Used in NASAP Reports Except Where Noted Under "Source"	Exceptional Scaling Factor (x)	Source
All categories for reprocessing plants	0.35	NASP
All capital categories for all contact-handling (C) fab plants	0.60	NASP
Base facility category for RO/CM and RO/RM plants	0.80	NASP
Base equipment category for RO/CM and RO/RM plants	0.70	NASP
Preoperational category for capital	0.70	SA&I authors
Expendable materials and hardware for all type plants	1.00	NASP
Recurring operating costs including personnel	0.80	NASP
Capital replacements	0.70	SA&I authors
Annual D&D cost	0.80	SA&I authors
Module D1-1 LWR fuel fab facility is a type C, CAT-III facility; values in red text		
C Contact-handled fuel facilities. RO/CM Remote operations/contact maintenance fuel facilities. RO/RM Remote operations/remote maintenance fuel facilities.		

For each non-reference PHWR-UOX fuel production rate, a new set of base FC costs was calculated using the cost scaling equation and above factors. Using the same G4-ECONS based model as that for the reference throughput results in a new table of annualized cost. Each of these non-baseline costs is divided by the non-baseline production rate to obtain the capital recovery, recurring cost, and D&D components of the non-reference overall levelized unit cost in $/kgU. These are merely added to obtain the new total unit cost which appears in Figure D1-7.5 for a throughput range of 50 to 2,000 MTU/yr. The figure also shows a plot of this data.

	Capacity in MTU/yr	2017 $/kgU
	50	326
	100	274
	200	236
	300	219
	400	207
	480	201
ref cap>:	520	198
	750	187
	1000	179
	2000	167

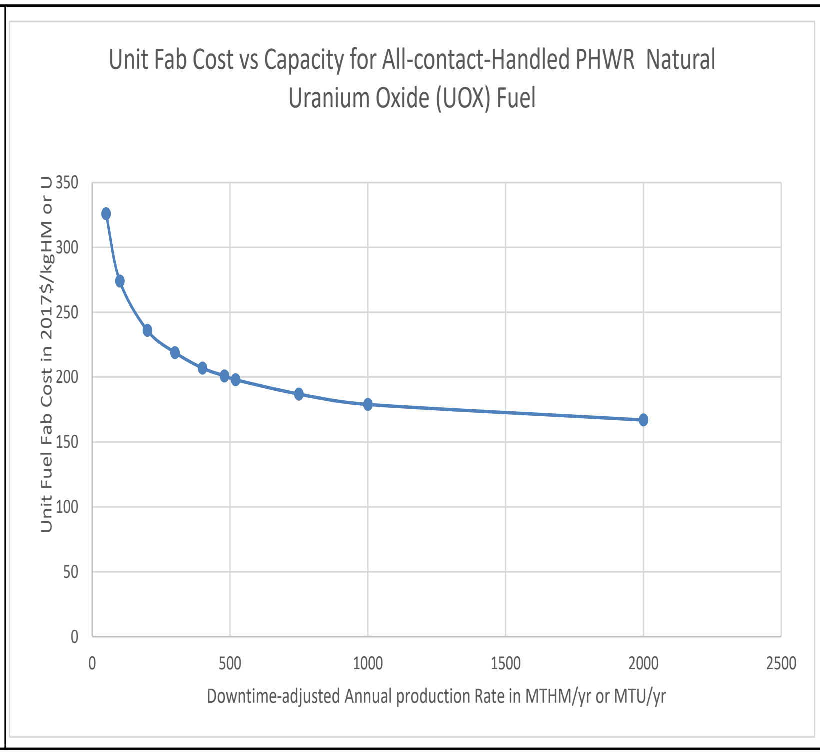

Figure D1-7.5. Levelized unit cost in $/kgU versus PHWR fuel fabrication plant production size also known as adjusted capacity or throughput.

In reality, the unit cost versus throughput curve would not be so smooth in appearance, since fuel fabrication plants are usually designed for an integer number of production lines of an optimized size each. The general curvature of the plot would have more of a stairstep appearance. Neither the 1978 analysts for the NASAP reports nor the SA&I author of this report had enough design data to develop a more accurate unit cost versus throughput sensitivity study.

D1-7.10. DATA LIMITATIONS

The reliability of the cost data is good, since PHWR-CANDU-UOX fuel production is a fully commercialized operation utilizing mature manufacturing technology.

D1-7.11. COST SUMMARIES

This last cost data section summarizes the WIT levelized unit cost data for the fabrication of PHWR fuel from the last few versions of the AFC-CBR, and it also provides the new WIT values in both 2017 USD (cost basis for all 2018–2021 NASAP-informed calculations for all fuel types) and 2020 USD (base constant USD costing year for this update). A general inflation factor of 1.04 is used to escalate from 2017 to 2020 USD. No incremental escalation based on process-related or regulatory factors is assumed.

2009 AFC-CBD Summaries. The module cost information is summarized in the WIT cost summary in Table D1-7.15 The summary shows the reference cost basis (constant year USD), 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.

Table D1-7.15. Cost summary table for CANDU ACR-700 PHWR-UOX fuel (2009 AFC-CBD).

WIT Table (2009 USD)			
Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Unit cost=$135/kgU	$115/kgHM	$155/kgHM	$135/kgHM
No new fab plant capital cost data identified for 2009 AFC-CBR.			

2012 AFC-CBD Update Summaries. The following WIT values and a corresponding probability distribution shape are recommended for use in future FC studies (Table D1-7.16).

Table D1-7.16. WIT CANDU fuel unit fabrication costs (2012 AFC-CBD update).

Fuel Type	Low Value (2012 $/kgHM)	Nominal Value (2012 $/kgHM)	High Value (2012 $/kgHM)
Pelletized Natural UO_2 Ceramic PHWR Fuel	115	200	300
Pelletized UO_2 Ceramic CANDU Fuel (RU From LWR Spent Fuel Reprocessing or SEU)	150	260	390

For uncertainty analyses, triangular distributions should be used with the values in the table rows above. The unit fabrication cost values for NATU-derived CANDU fuel in Table D1-7.16 were calculated by using similar multipliers (2012 AFC-CBR to 2009 AFC-CBR) to those used for LWR virgin-UOX derived fuel. As explained above, this is because of similarities in the LWR and CANDU fuel production, institutional, and regulatory environments. A sustained increase in the price of zirconium is factored into the 2012 AFC-CBR assumptions.

For the new category of RU-derived CANDU fuel, a 30% penalty is added to all three cases (low, nominal, and high) per the hypothetical case in (Del Cul et al. 2009). The same 30% factor is suggested for CANDU fuel made from SEU. This accounts for the more stringent safety and security environment associated with enriched U use.

D1-7.11.1 2017 AFC-CBR Summaries

Table D1-7.17 shows the 2012 update values escalated to 2017 USD using an escalation factor of 1.09. No new CANDU technical cost baseline information on PHWR-UOX was gathered in the 2012–2017 timeframe. These are the values appearing in the last published AFC-CBR document (Dixon et al. 2017).

Table D1-7.17. WIT CANDU fuel unit fabrication costs (escalated to 2017 USD).

Fuel Type	Low Value (2017 $/kgHM)	Mode Value (2017 $/kgHM)	Mean Value (2017 $/kgHM)	High Value (2017 $/kgHM)
Pelletized Natural UO_2 Ceramic CANDU Fuel (PHWR-UOX)	125	218	224	327
Pelletized UO_2 Ceramic CANDU Fuel (RU from LWR Spent Fuel Reprocessing or SEU)	164	284	291	425

D1-7.11.2 2021 AFC-CBR Summaries Based in Part on New NASAP-Informed Analyses

No new PHWR-UOX literature or trade press pricing data has been identified since 2017, so the 2017 USD values above in Table D1-7.17 are escalated by 4% to convert them to 2020 USD. These 2020 USD values could stand as the literature-based WIT values of 130 $/kgU (low), 227 $/kgU (mode), 340 $/kgU (high), and a mean of 233 $/kgU for PHWR-NATUOX. For PHWR SEUOX, the equivalent 2020 USD values would be 171 $/kgU (low), 295 $/kgU (mode), 442 $/kgU (high), and a mean of 303 $/kgU. In selection of the final 2020 USD PHWR fuel WIT values below, these literature-based prices will be considered in addition to the calculated unit cost values derived from the NASAP study.

Inclusion of NASAP-Based Data. Now that we have presented in detail the NASAP and G4-ECONs LCC models developed by ORNL in 1978 and SA&I in 2018–2021, we can add this new PHWR unit fabrication cost information to the overall data set to produce a new, updated PHWR fuel WIT table. It has already been determined that the 520 MTU/yr reference case, calculated levelized unit cost value of 198 $/kgU (2017 USD) or $206 $/kgU (2020 USD) fits well within the range of the price data in the paragraph above. For larger plants of 1,000 to 1,500 MTU/yr, which are more likely for new greenfield facilities, the Figure D1-7.3 graph indicates that lower unit costs of 167 to 192 $/kgU (2017 USD) or 174 to 200 (2020 USD) are possible. Table D1-7.18 shows the updated 2017 USD and 2020 USD WIT unit fabrication cost values for this Module D1-7.

Table D1-7.18. FY-21 Module D1-7 what-it-takes levelized unit fabrication costs for LWR-UOX ceramic fuel (technical basis 2017 USD escalated to 2020 USD).

Fuel Type	Reference Cost if Available	Low	Mode	High	Distribution Type	Calculated Mean
Std PHWR UOX (natural UOX) ($/kgU)	198 (NASAP-informed)	125	200	300	Triangular	208
2020$	–	132	210	316	–	219
Front-end deconversion adder to obtain SEU case below ($/kgU)	–	30	47	60	Triangular	46
2020$	–	32	49	63	–	48
PHWR-SEU from reprocessed PWR-UOX SNF	N/A	155	247	360	Triangular	254
2020$	–	163	260	379	–	267
Escalated from 2017$ estimates with 5.2% escalation to 2020$ then rounded to the nearest 50. Mean is average of (high, low, mode).						

For this update, a mode (most likely) value of $200/kgU (2017 USD) for standard natural-assay PHWR UOX was selected, since it represented a credible base case derived from the bottom-up NASAP study. It is lower than the 2017 AFC-CBR value of $218/kgU derived from literature surveys and opinions. The NASAP-informed low and high ranges—125 and 300 respectively in 2017 USD—for PHWR-UOX were derived from examination of NASAP cost/capacity scaling relationships and fall entirely with in the previous 2017 AFC-CBR WIT range of 125–307 $/kgU (2017 USD).

To obtain the cost of producing SEU PHWR-UOX fuel, the cost of deconversion must be added in, since the feed to the plant will likely be virgin $SEUF_6$ from an enrichment plant or a reprocessing plant that has the capability to fluorinate the separated REPU product; if the latter, the fluorination step also removes most of the trace fission product or trace transuranic waste (TRU) radionuclides that would pose personnel radiation protection measures beyond the usual contact-handling ones during refabrication. It was determined from ORNL/TM-6501 data that deconversion accounts for 14% of the unit cost of fabricating PWR-UOX fuel—derived by calculation of deconversion unit operations capital costs as a fraction of the total unit operations capital, and assuming this same unit operations partitioning fraction applies to capital cost distributables such as contingency and indirects, and to personnel-related annual costs. For the reference PWR-UOX case, this is 14% of $334/kgU or $47/kgU in 2017 USD. This amount can be added to the natural UO2 feed PHWR-UOX case to obtain the SEU-PHWR-UOX case. A set of WIT values for the adder were selected by the SA&I author, and they are in the second data row of Table D1-7.18. To obtain the WIT values for SEU PHWR-UOX, the first two data rows in the table above are added. Note that this more rigorous method of calculating the NATU to SEU adder replaces the 30% adder described in the 2012 AFC-CBR.

The triangular distributions based on the PHWR unit fabrication costs in the above WIT table are shown in Figure D1-7.6 and Figure D1-7.7. Both relative and cumulative probability distributions are shown. This probabilistic data is very useful for FC economic models where cost uncertainty is a major consideration.

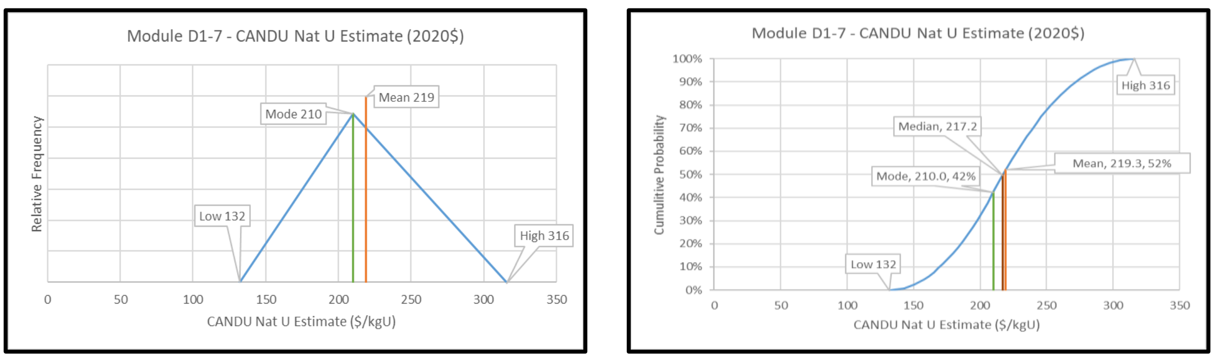

Figure D1-7.6. Reference PHWR-UOX fuel fab (standard CANDU natural UO2) estimate (2020 USD).

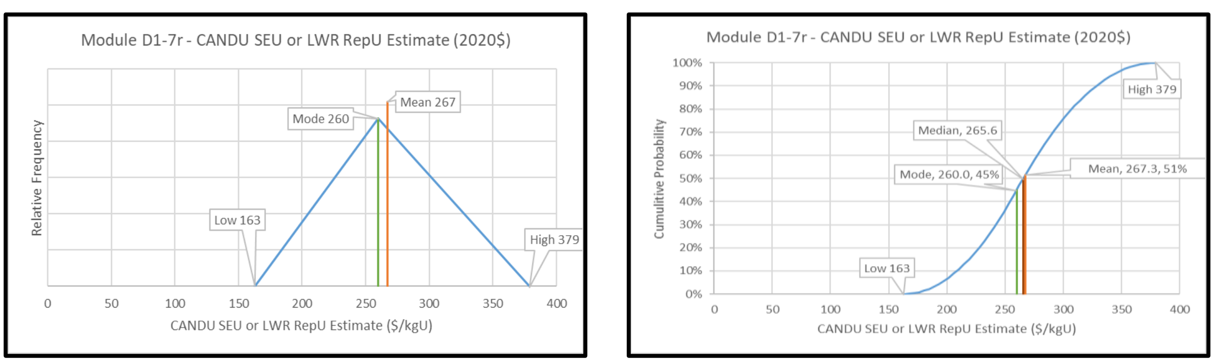

Figure D1-7.7. Reference PHWR SEUOX fuel fab estimate (2020 USD).

D1-7.12.SENSITIVITY AND UNCERTAINTY ANALYSIS

A unit fabrication cost versus production capacity dataset and curve was generated using the escalated NASAP-LCC information and the G4-ECONS-based levelization and annualization algorithms created by the SA&I authors. Because of the high technical readiness level of this fuel fabrication technology, no studies other than plant LCCs versus production capacity were performed. PHWR fuel fabricators have likely done additional studies on fuel design changes for CANDU ATFs; however, these are likely to be proprietary. Among these could be using plutonium or thorium for MOX-based PHWR fuel.

D1-7.13.REFERENCES

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