NERAC Briefing: Assessment of Dose of Closed vs Open Gen-IV Fuel Cycles

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Public Dose and Worker Dose Comparison of Open vs Closed Fuel Cycles

- *Gen-IV fuel cycle options are meant to address all stated Gen-IV Goals*
  - *Dose to workers and to the public is one of the numerous elements to be evaluated by Gen-IV R&D*
  - *The Fuel Cycle Crosscut Group was assigned to take an early look at dose implication tradeoffs of open and closed fuel cycles*
- *FCCG Interpretation of Assignment:*
  - *Collect already-existing evaluations and prepare a briefing on what is currently known*

Approach

- *Look at Actual Historical Doses Based on Operational Experience*
  - *Data compiled by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for many decades*
    - *Once-thru*
    - *MOX Mono Recycle*
  - *UNSCEAR data is for public dose and worker dose*
    - *By link in the fuel cycle (e.g., mining, milling, fab, etc.)*
    - *Normalized per GWe year of delivered energy*

(2) Look at Projected Future Dose Contributors for several Potential Closed Fuel Cycles

- *Data taken from fuel cycle parts of OECD-NEA Study: Accelerator Driven Systems and Fast Reactors in Advance Fuel Cycles: A Comparative Study (2002)*
  - *Closed Multi Recycle Fast Reactor Fuel Cycles fed by LWR Discharge Fuel*
    - *MOX Multi Recycle*
    - *TRU Multi Recycle*
  - *Effects on Operations Dose Source Terms*
  - *Effects on Legacy Dose Source Terms*

(3) The Issue for Evaluation:

- *Do we see any indication from already available information that would make dose considerations dominate over other considerations in future selections of Gen-IV fuel cycle choices (i.e., are fuel cycle options constrained by Dose Considerations?)*

Historical Operational Data

Measures of Human Exposure to Ionizing Radiation

- *United Nations Scientific Committee on The Effects of Atomic Radiation*
  - *UNSCEAR Report to General Assembly 2001*
  - *The data presented here come from their report*
- *"Dose" measures exposure of living tissue to ionizing radiation*
  - *Unit of dose is gray (Gy)*
- *Biological effect per unit of dose varies with radiation type and cell type*
  - *Unit of "effective dose" is sievert (Sv)*
- *For a defined population group exposed to dose (e.g., public or workers)*
  - *Unit of "collective effective dose" is man Sv*
    (i.e., summed over exposed individuals – applies to public population doses)
  - *Unit of individual dose for each member of group is* $\dfrac{\text{collective man Sv}}{\text{\# individuals in the group}}$
    (applies to average individual dose – either member of public, or worker)
- *Radioactive Source Strength*
  - *Unit of measure is #disintegrations/sec* $1\dfrac{\text{dis}}{\text{sec}} = 1\text{becqueral(Bq)}$

Individual Average Effective Dose to the Public from Natural Plus Man-Made Sources

Table 4
Annual per caput effective doses in year 2000 from natural and man-made sources

Source	*Worldwide annual per caput effective dose (mSv)*	*Range or trend in exposure*
Natural background	2.4	Typically ranges from 1-10 mSv, depending on circumstances at particular locations, with sizeable population also at 10-20 mSv.
Diagnostic medical examinations	0.4	Ranges from 0.04-1.0 mSv at lowest and highest levels of health care
Atmospheric nuclear testing	0.005	Has decreased from a maximum of 0.15 mSv in 1963. Higher in northern hemisphere and lower in southern hemisphere
Chernobyl accident	0.002	Has decreased from a maximum of 0.04 mSv in 1986 (average in northern hemisphere). Higher at locations nearer accident site
Nuclear power production (see paragraph 34)	0.0002	Has increased with expansion of programme but decreased with improved practice

- By far the greatest contribution to exposure comes from natural background radiation. The annual per caput dose is 2.4 mSv and the range in typical circumstances may be between 1 mSv and 10 mSv. There are, however, small groups of persons who may be exposed to much higher levels. In some places, the natural radionuclide content in the soil creates high external exposure levels; these are known as high-background areas. Much more significant and wide-spread is the variability in the levels of radon concentration in indoor air.
- The second largest contribution to exposures of individuals worldwide is from medical radiation procedures. There is an increasing trend in such exposures, reflecting the more widespread use and availability of medical radiation services throughout the world.

Observation:

- Nuclear could increase deployment by a factor of 2000 before producing a dose contribution comparable to the public's elective choice to benefit from nuclear medicine

The Nuclear Fuel Cycle: Collective Public Effective Dose Per Year Per Unit Energy By Link in The Fuel Cycle

Table 45
Normalized collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle [a]

Source	Normalized collective effective dose [man Sv (GW a)⁻¹]				
	1970-1979	*1980-1984*	*1985-1989*	*1990-1994*	*1995-1997*
Local and regional component					
Mining	0.19	0.19	0.19	0.19	0.19
Milling	0.008	0.008	0.008	0.008	0.008
Mine and mill tailings (releases over five years)	0.04	0.04	0.04	0.04	0.04
Fuel fabrication	0.003	0.003	0.003	0.003	0.003
Reactor operation					
Atmospheric	2.8	0.7	0.4	0.4	0.4
Aquatic	0.4	0.2	0.06	0.05	0.04
Reprocessing					
Atmospheric	0.3	0.1	0.06	0.03	0.04
Aquatic	8.2	1.8	0.11	0.10	0.09
Transportation	<0.1	<0.1	<0.1	<0.1	<0.1
Total (rounded)	12	3.1	0.97	0.92	0.91

a Analysis is based on reported releases per unit electrical energy generated and presently adopted dose coefficients. These results may, therefore, differ somewhat from earlier evaluations by the Committee.

Observations

Within the Context that:

• Nuclear power production effects are 4 orders of magnitude down from natural background to individual members of the public

Then, collective dose contributions by link in cycle:

• Power Plant dominates By a Factor of 2
• Mining is Next
• MOX Mono recycle is 2/3 of mining
• A factor of >10 reduction has been achieved over 3 decades of industry improvement in operations and technology

Individual Average Effective Dose to Workers in Various Industries

8 REPORT TO THE GENERAL ASSEMBLY

Table 3
Occupational radiation exposures

Source / practice	*Number of monitored workers (thousands)*	*Average annual effective dose (mSv)*
Man-made sources		
Nuclear fuel cycle (including uranium mining)	800	1.8
Industrial uses of radiation	700	0.5
Defence activities	420	0.2
Medical uses of radiation	2 320	0.3
Education/veterinary	360	0.1
Total from man-made sources	4 600	0.6
Enhanced natural sources		
Air travel (crew)	250	3.0
Mining (other than coal)	760	2.7
Coal mining	3 910	0.7
Mineral processing	300	1.0
Above ground workplaces (radon)	1 250	4.8
Total from natural sources	6 500	1.8

Observations

- Nuclear Industry Workers receive annual doses on average which are similar to other industries
  - Less than miners
  - Less than air crews

Summary of Observations of Actual Historical Experience

Public Dose:

- *Natural Sources dominate effective dose to the public*
- *The range of geographical viability of natural effective dose dominate the sum of all man-made effective dose contributors to the public*
- *Of man-made contributors to average individual public dose*
  - *Diagnostic medical procedures dominate by a factor of 100 or greater over all other man made sources*
  - *Nuclear power production is a factor of 2000 less than Medical Diagnostics*
- *Within this overall context, The Nuclear Energy Fuel Cycle Chain*
  - *Specific Contributions to Collective Public Doses (man Sv/GW_a)*
    - *Dominated by Reactor Operation*
    - *Mining is < ½*
    - *Reprocessing is < 1/3*

Nuclear Industry Individual Worker Dose

- *Occupational Dose to Nuclear Workers*
  - *In same range as other industries*
    - *Nuclear medicine*
    - *Radiography*
    - *Miners*
    - *Pilots and Crew*
  - *Specific link in cycle to Worker Dose (Sv/GW_a)*
    - *Dominated by Mining + Milling*
    - *Reactor Operation is factor of 5 less*
    - *Reprocessing is also factor of 5 less*

- *In Summary*
  - *Collective public affected most by reactors*
  - *Individual Nuclear Workers affected Most by Mining/Milling*
  - *Public impact << Elective Nuclear Medicine; Nuclear Worker $\lesssim$ other elective industries*

Projected Future Dose Contributors

Gen-IV Candidate Fuel Cycles

- ***Candidate Gen-IV Fuel Cycles include***
  - ***Open Cycles***
  - ***Closed Cycles***
  - ***Symbiotic Cycles: Open Cycles □ Closed Cycles***
- ***The Nub of The Dose Element Tradeoff among Open and Closed Cycles***
  - ***Closed fuel cycles offer a potential to affect dose source terms***
    - ***To Miners***
    - ***In legacy stockpiles of mill tailings and nuclear waste***

  But introduce new steps in the fuel cycle which might increase dose exposures to nuclear workers or the public

    - ***Recycle Step***
    - ***Refabrication Step***
- ***Is dose consideration on Fuel Cycle Choice – likely to constrain Gen-IV Options?***

Dose Related Aspects of Closed Fuel Cycles

On the Positive Side of the Tradeoff, per Unit of Energy Benefit

- ***Closed Cycles hold potential to:***
  - ***Reduce the amount of material consigned to waste having long-lived heat emission – perhaps easing environmental conditions on the barriers***
  - ***Reduce the amount of material consigned to waste having long-lived radioactivity (e.g., affect the source term component of future public dose risk***

(future dose risk) a (Source Term) * { Estimated Probable Effectiveness of Engineered & Natural Barriers }

  - ***Extract more energy per unit of mining/milling exposure to public and workers***

On the Negative Side of the Tradeoff, per Unit of Energy Benefit

- ***Close Fuel Cycles***
  - ***Introduce a recycle and a refabrication step into the fuel cycle having potential for dose exposures to workers and the public***
  - ***New fuel types to be handled to and from the reactor***

The OECD-NEA has recently completed a detailed study

  - ***Contains data relevant to the Net of the Tradeoffs for some but not all Gen-IV concepts***

The OECD-NEA Study of Symbiotic Closed Fuel Cycles Operating in Mass Balance

- ***Steady State Energy Park of Thermal reactors with discharged fuel feeding fast reactors***
- ***All Energy Parks Deliver the Same Energy Annually***
- ***Closed Cycle Fast Neutron Burner reactors Consume the Transuranics from Thermal Reactors***
- ***The Energy Fractions of Thermal and Fast Systems are chosen to Balance The Mass Flows***

Park	% of Energy		Sent to Waste = x			
	Thermal	Fast	U	Pu	MA	FP
a. Once-Thru LWR-UOX	100	0	x	x	x	x
b. LWR-UOX ? LWR MOX ? FR MOX Mono Recycle Multi Recycle	80	20	+	*	x	x
c. LWR-UOX ? FR TRU Multi Recycle	65	35	+	*	*	x
d. FR TRU Multi Recycle	0	100	§	*	*	x

+ = Recovered and put in interim storage

* = Trace losses assumed @ 0.1% per recycle pass

§ = Recycled

OECD-NEA: Tradeoff Outcomes

- *They found that compared to Once-Thru (a)*

	Potential Benefit		Potential Operations Impact
	Front End	Back End	
	Reduced Mining	Reduced Long Term Dose Source Term	Radioactivity Of Feedstocks Bq/kg
Case (b)	~30%	< x 10	~ Same as LWR-MOX
Case (c)	~37%	x about 100	Shielded Remote Refab Req'd
Case (d)	~200	x about 100	Shielded Remote Refab Req'd

OECD-NEA Study: Increased Feedstock Radioactivity for Pu + Minor Actinide Recycle

Refabrication Step (per Kg basis)

		(b)	(c)	(d)
	LWR-MOX	Pu Burner (FR)	TRU Burner (FR)	Fast Reactor
Activity (10^{12} Bq/kgHM)				
Actinides	38	148	111	29
Decay heat (W/kgHM)				
Actinides	1.94	9.64	33.79	5.79
Neutron Source	0.10	0.66	92.05	9.76

Recycle Step (per Kg basis)

		(b)	(c)	(d)
	LWR-MOX	Pu Burner (FR)	TRU Burner (FR)	Fast React or
Fuel cooling time (a)	7	7	2	2
Actinides and FPs FPs	50.30 17.26	157.0 62.38	232.4 155.3	160.4 131.7
Decay heat (W/kgHM)				
Actinides and FPs	6.31	21.77	46.00	18.56
FPs	1.41	4.86	15.34	12.88
Neutron source strength (106 n/s kgHM)				
Total	10.93	39.28	86.08	9.76

- Recycle step: < x 10 increases compared to LWR MOX
- Refabrication step: < x 10 compared to LWR MOX
  : significant neutron increase
- Shielded Remote Refabrication will be required for Pu + Minor Actinide Multi Recycle

Briefing Summary

- ***Current Open Fuel Cycles***
  - ***Expose the Public ~10^{-4} of background***
  - ***Public exposures are ~2000 times below dose exposures from elective diagnostic medicine***
  - ***Nuclear workers ~ same as other industries such as airline crews, miners***
- ***Gen-IV Options for Closing the Cycle***
  - ***Will be decided considering multiple Gen-IV goals***
  - ***Dose tradeoffs are one factor***
- ***Publicly Available Data on past performance of Open Cycles and Projected Performance of selected Symbiotic Closed Cycles was Examined***
  - ***Preliminary look does not indicate a potential showstopper among the subset of cases examined (all use fast multi recycle)***
  - ***Further R&D to address technology issues is included in the Roadmap***

Overview of Gen-IV Strategies Relevant to Dose from the Nuclear Fuel Cycle

Strategy	R&D Recommendation	Dominate Payoff	
		Public	Worker
• Open and Closed Cycle Strategies:			
- Increase Energy Benefit/Unit Fission	(TWGs)	x	x
• Higher conversion efficiency plants			
• Use of waste heat for additional benefit			
- Reduce Activation Products Production per Unit Energy			
• N-15 Enrichment of Nitride Fuel (less C^{14})	(TWGs)		x
• Less Corrosive Coolants (D&D dose reduction)	(TWGs)		x
(Maintenance reduction)			x
(Discharge reduction)		x	
• Open Cycle Strategies		x	x
- In situ Leaching & Other Reduced Labor Mining Methods	(FCCG)		x
- Increase discharge burnup	(TWG)		x
• More benefit per unit of fab and handling			x
- Multi-Purpose Casks			
• Less Worker Exposure from less SNF handling	(FCCG)		
- Reduced Heat Load Repository Designs			x
• Less Challenge to Assuring Impedance	(FCCG)	(reduced uncertainty)	
- Symbiotic Tie to Closed Cycles	(FCCG)		
• (See below)	(FCCG)		
• Closed Fuel Cycles			
- Total Fission Consumption of Actnides	(TWG//FCCG)		
• Reduced Mining/Unit of Energy Benefit			x
• Reduced Mill Tailings		x	
• Shorter duration of Source term in Repository		(reduced uncertainty)	
(How: higher discharge burnup and/or smaller losses per recycle pass)			
- Capture and Sequester Noble Gas Fission Products	(FCCG)		
• C^{14}, Kr^{95}, H^{3}, etc.Higher conversion efficiency plants		x	
- Reduce Production of Secondary Waste per Unit Recycle	(FCCG)	x	
- Customized Waste Forms	(FCCG/TWG)		
• Tailored to geochemical behavior of specific waste elements (Te, I, Np)		x	