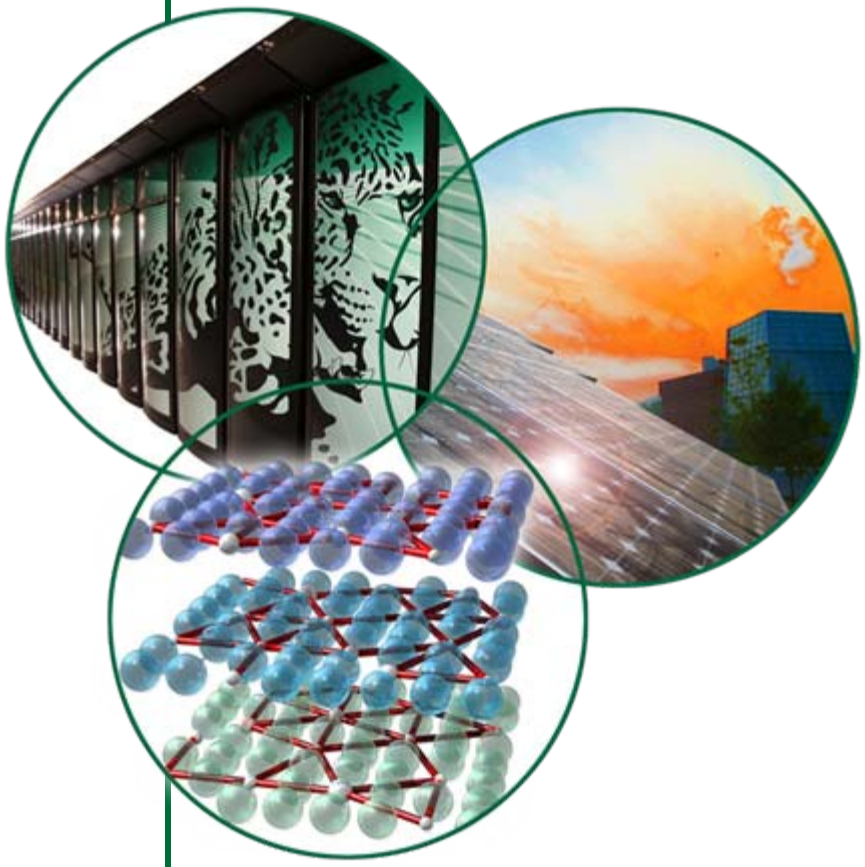
Nuclear Fuel

Is there anything new under the sun?

Brian Cowell

Manager, Russian Plutonium Disposition Program

GNSTD



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

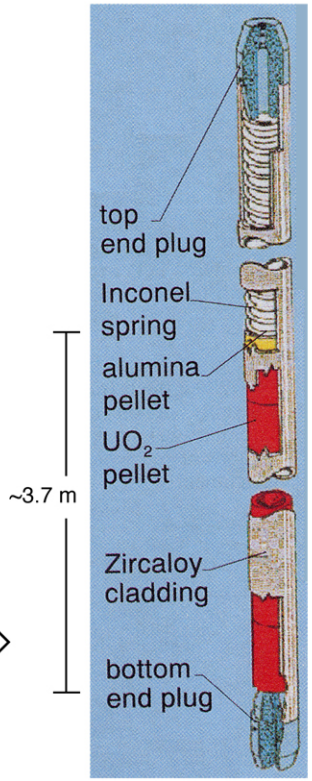
- Nuclear fuel fundamentals – an introduction
- Current nuclear fuel
- Problems with current fuel (focus of current research)
- Near-term developments
- Distant future (hopes and dreams)

Fuel Is "Active" Part of Reactor

- High atomic mass nuclei (primarily ^{235}U and ^{239}Pu) undergo fission
- Each fission releases
  - ~200 MeV of energy, and
  - fission products.
- Competing reactions also generate higher actinides (minor actinides)
- Need gas-tight barrier (cladding) around fuel for containment of fuel, fission products, and higher actinides

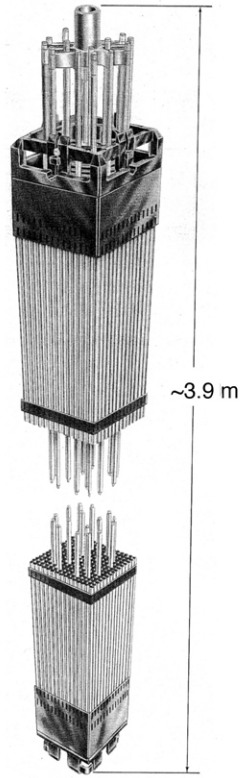
Three Key Parts Are Pellet, Element/Rod/Pin, and Assembly

Fuel
(UO_2 for example)



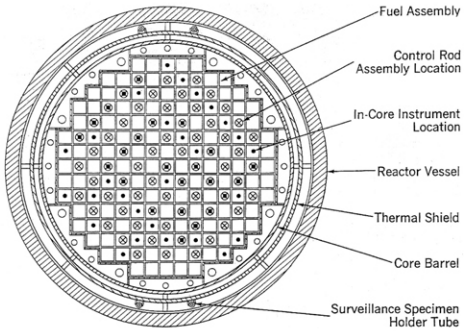
Cladding
+
360-380 Fuel Pellets

Fuel Element



60-300
Fuel Elements

Fuel Assembly



100's of Fuel Assemblies

Reactor Core

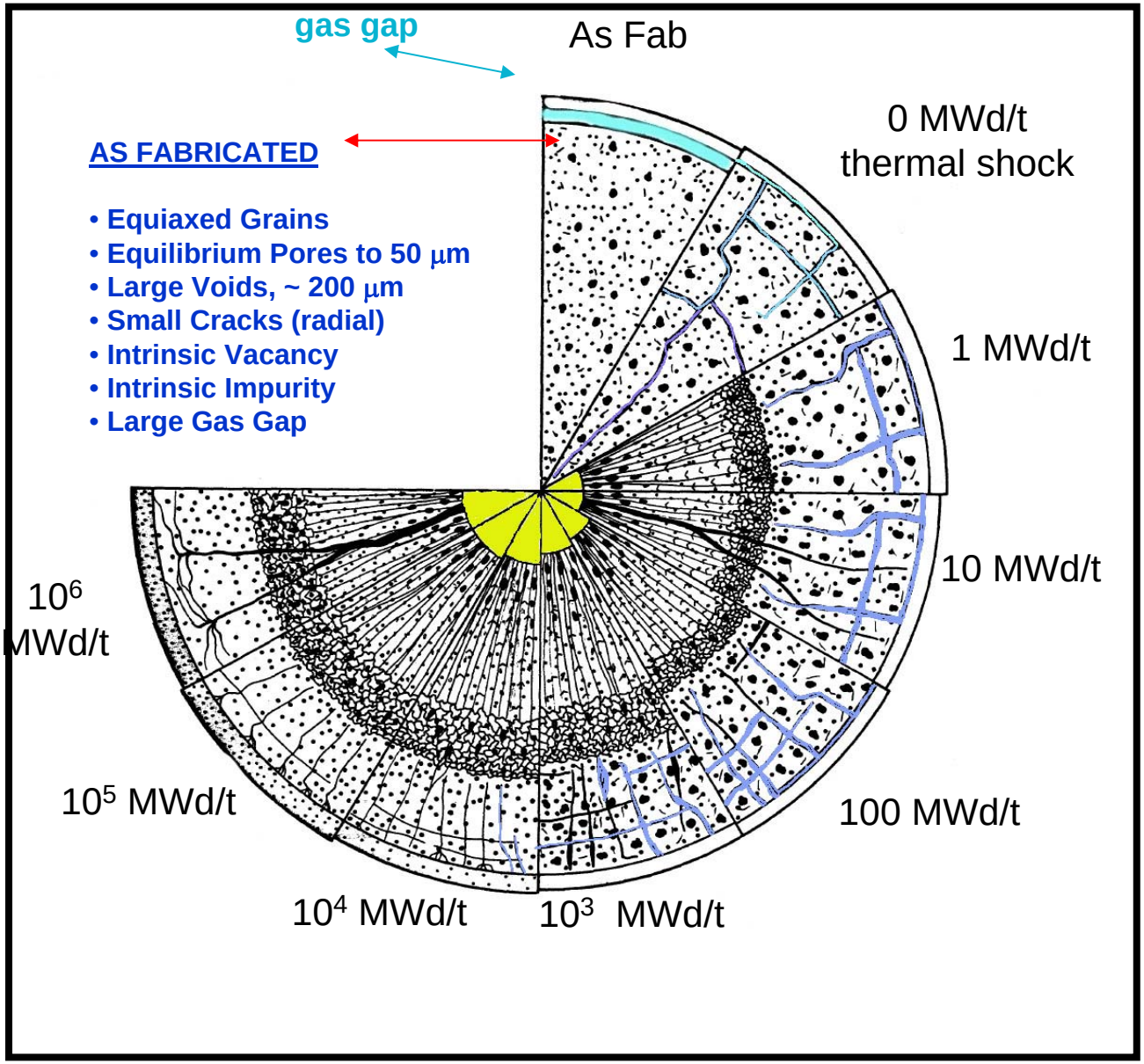
Following Considerations Impact Selection of Fuel Material

- Sufficient geometric stability during operation
- Satisfactory thermal properties during operation
- Acceptable chemical compatibility with cladding
- Adequate fissile atoms density
- Sufficient chemical compatibility with coolant, in case of clad breach
- Compatibility with rest of fuel cycle

Following Considerations Impact Selection of Cladding Material

- Mechanical properties required for operating conditions (strength, creep, etc.)
- Satisfactory chemical compatibility with coolant
- Acceptable chemical compatibility with fuel
- Sufficient resistance to irradiation effects (embrittlement, swelling, etc.)
- Low neutron cross section

Meticulously Controlled Initial State Almost Immediately Destroyed During Irradiation



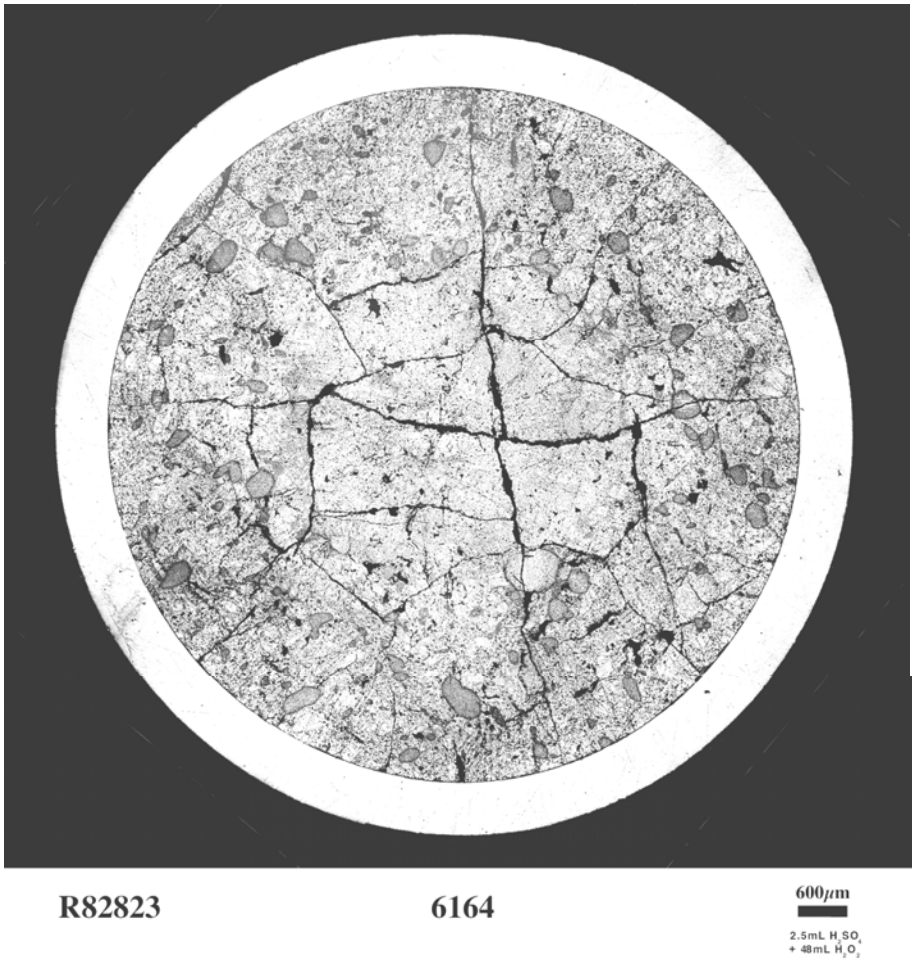
AS FABRICATED

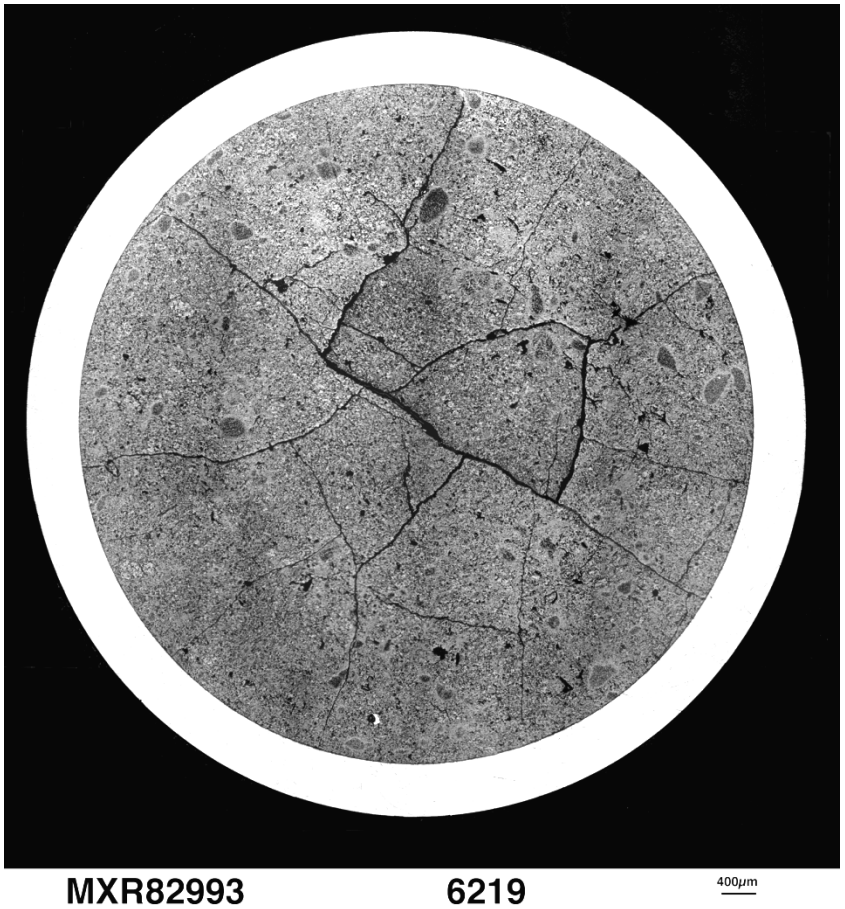
- Equiaxed Grains
- Equilibrium Pores to 50 μm
- Large Voids, ~ 200 μm
- Small Cracks (radial)
- Intrinsic Vacancy
- Intrinsic Impurity
- Large Gas Gap

AS IRRADIATED

- Crack Evolution
- Radiation Defects
  - Vacancy/Interstitial
  - Dislocations
  - Small Clusters
  - Voids (central void)
- Columnar Grain Growth
- Grain boundary
  - Carbide formation
- Equiaxed Grain Growth
- Metallic Inclusion
- Solid Solution Impurity
- Second Phase Formation
- Evolving gas conduction

This Restructuring Can Be Readily Observed During PIE





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Nuclear fuel – commercially today – almost by default means low-enriched uranium oxide in zirconium-alloy tubes

- This UOX used in almost all world's PWRs, BWRs, PHWRs, and RBMKs
- Mostly produced through enrichment of natural uranium (~65,000 MT/yr natural U/yr)
- Supplemented with limited addition of recycled (reprocessed) uranium (only about 2500 MT/yr nat-U equivalent)
- Natural uranium reserves more than adequate to fuel likely nuclear power programs over the coming decades

Low-enriched UOX pellets in zirconium-alloy tubes not ideal

- Has notable technical disadvantages, including
  - Low thermal conductivity, resulting in high centerline temps
  - Burnup limited to only about 5% (currently) of initially loaded HM
- However, over past sixty years, has been refined to such an extent that
  - It is very reliable (about 1 failure per million)
  - It is relatively inexpensive and mass-produced (~ commoditized)
  - Generally meets needs of utility customers, and no incentive to try for radical advancements

But…It is very expensive and time consuming to qualify new fuel, especially anything other than incremental change

- Need materials testing
- Need irradiation testing (research reactors)
- Lead test assemblies (few, perhaps multiple sets, in power reactor)
- Batch loading

>$100M

Nuclear fuel makes up a small part (<20%) of overall busbar cost of nuclear electricity production

- Thus, there is no overarching economic incentive to take risks with advanced fuels
- Risk (technical and licensing) and potential costs of failure outweigh potential savings, in most cases
- Only small incremental (low risk) advances are pursued vigorously
- Significant changes to front end or back-end costs ($0.001/kW-h NWPA fee) may change this economic situation at some point in future

Mixed uranium-plutonium oxide (MOX) fuel is next most common fuel in terms of volume

- Uses fissile isotopes of plutonium to replace U-235
- Pellets, rods, and assemblies are really not very different from LEU and perform similarly
- Historically, was to conceived to be a “stepping stone” or temporary fix to bridge gap to plutonium fuel cycle with fast reactors
- At currently anticipated U prices, MOX presents clear commercial disadvantages
- Implemented primarily for reasons other than economics (energy self-sufficiency, sustainability)
- Only a few hundred fuel assemblies/yr (few % total)

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After years of dedicated R&D, performance of UOX fuel greatly optimized

- Nevertheless, goal of “perfect” fuel not yet achieved
- Some failures continue, due to:
  - Fretting (debris and grid)
  - Water side corrosion

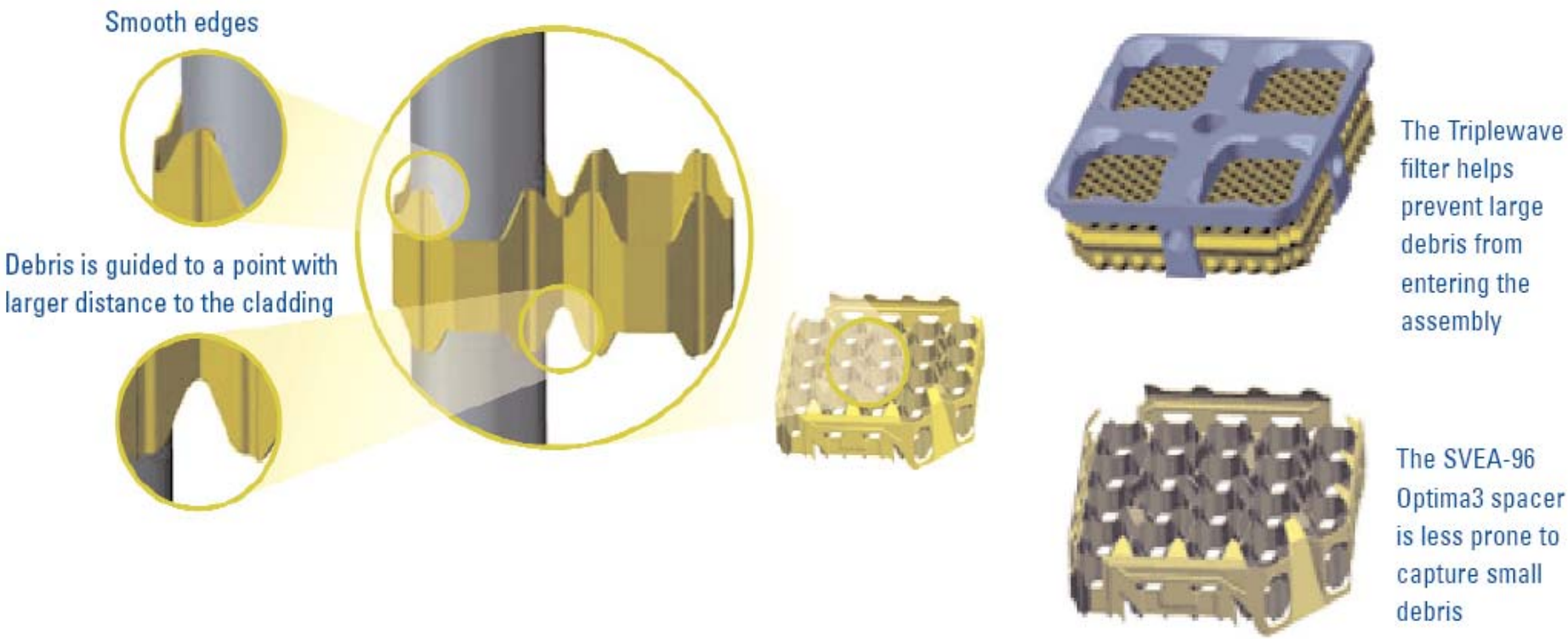
Debris fretting situation improving, through control of foreign objects and through assembly design

Debris found in a feedwater heater where a fretting fuel failure occurred

Managed by UT-Battelle
for the U.S. Department of Energy

Source, July 09: www.gepower.com/prod_serv/products/nuclear_energy/en/downloads/def_deb_filter.pdf

Filters now incorporated into lower portion of fuel assemblies

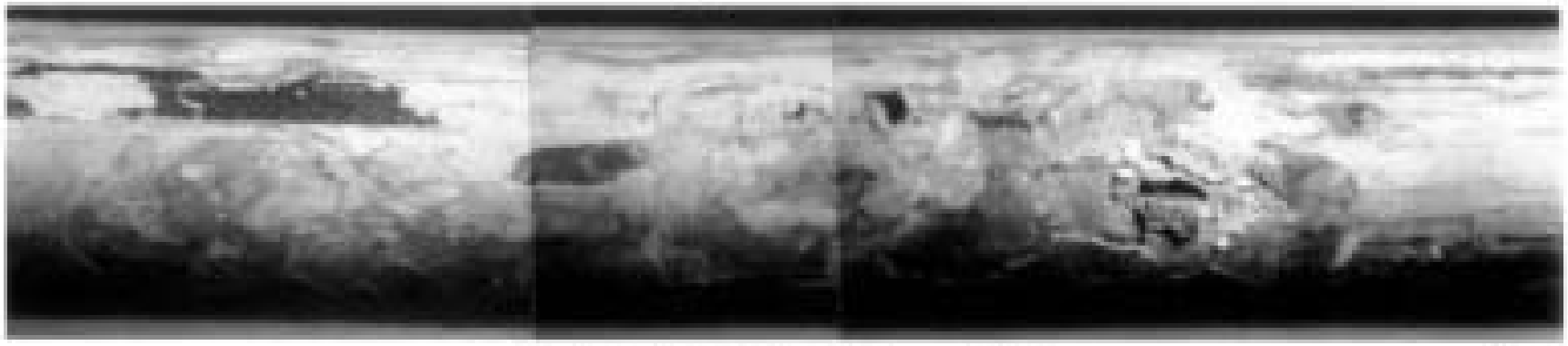


Source July 09: www.westinghousenuclear.com/Products_&_Services/docs/flysheets/NF-FE-0015.pdf

Unfortunately, coolant must enter assembly - thus debris fretting not yet eliminated

Source July 09: www.gepower.com/prod_serv/products/nuclear_energy/en/downloads/def_deb_filter.pdf

Unusual corrosion due to water-chemistry problems also continues



300° at 117"-119.3" from BEP

Mild Oxide Damage

Crud-enhanced corrosion can be severe

Figure 1 Crud deposit on a one cycle high duty bundle at River Bend end of cycle 8

Figure 2 Tenacious crud deposit and localized cladding perforation of River Bend one cycle fuel at end of cycle 8

Bottom line – UOX fuel performance very good

- Fuel failures are now big news (uncommon)
- Remaining failures are not safety issue, but economic issue and perception problem
  - EPRI estimates *$40-80M* per event for lost generation, inspection, replacement fuel, etc.
- Efforts to reduce failures continue, through initiatives such as EPRI's "Zero by 2010"

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Past as prologue…

- For past twenty years at least, focus has been on slow, incremental improvements in
  - cladding alloys,
  - pellet and cladding processing,
  - design (removing conservatisms),
  - manufacturing, and
  - operations (foreign object control, chemistry).
- This incremental approach probably to continue unabated for next twenty years or longer.

Beyond such incremental improvements, three fuels other than standard UOX/MOX are likely to be implemented over next 20 years

- Minor-actinide bearing fuels
- Vibration compacted particle fuel (vipac)
- Coated-particle fuel, for use in high-temperature gas reactors and possibly other applications

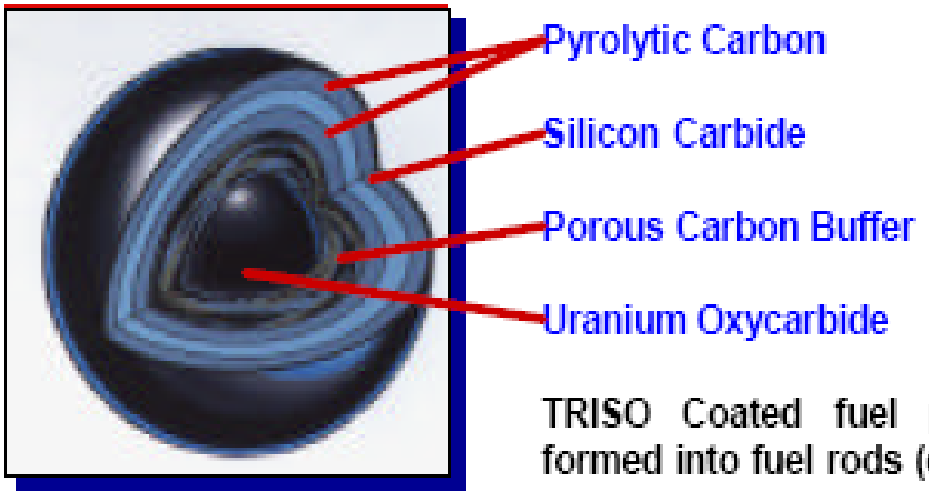
Minor actinide fuels – another whole world in and of itself

- Options range from minor Np-additions to “standard” MOX product to full inert-matrix minor actinide targets
- MA-MOX fuels and/or MA LWR targets are required if sustainability is to be achieved *in near term* because only LWRs exist in sufficient numbers
- AFCI program, one of DOE’s largest fuel programs, investigating various MA fuels, among other options
- May include zirconium-matrix metal alloy fuels as well

Vipac, based on NIIAR process, to be implemented for BN800 SFR in Russia

- Oxide granules (sand) produced from electrorefining in molten chloride salts
- Resulting oxide mass crushed and sieved
- Proper proportions mixed and loaded directly using multifrequency vibration
- Metal oxygen getter additive increases smear density
- Process to be used in pilot production facility (~10 MTHM/yr) in Russia within decade

Coated particle fuel development driven primarily by need for high-temperature nuclear process heat (NGNP and other similar HTGRs)



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

PARTICLES COMPACTS FUEL ELEMENT

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Beyond next 20 years, many additional opportunities available

- More exotic options have been proposed – “hopes and dreams” fuels
- Some, such as SiC clad on UN, have very high potential, but are far from commercial application
- Exotic options touted by proponents as “better than sliced bread” or “offering a solution to everything”
  - Often characterized by excessive marketing hype
  - Must sound far better than current fuel to generate interest in trying to topple dominance of UOX, a known product with a good track record
- With few exceptions, most of these options have already been researched, sometimes extensively, but history is forgotten or unknown or ignored
- Would like to provide two distinct examples, RTPI and more general ThO2 fuel

Radkowsky Thorium Plutonium Incinerator (RTPI) is poster child for hype over substance

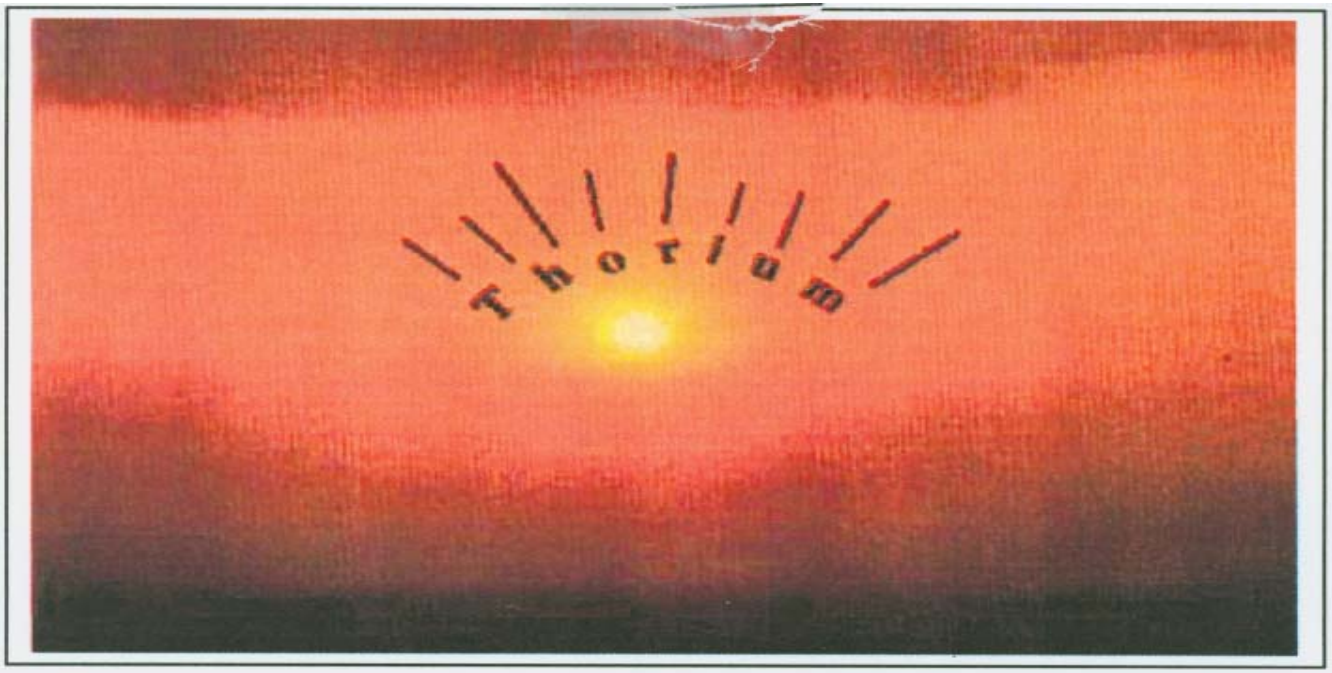
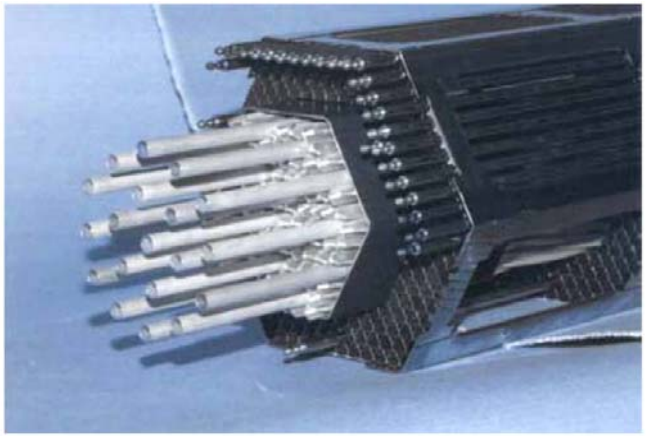


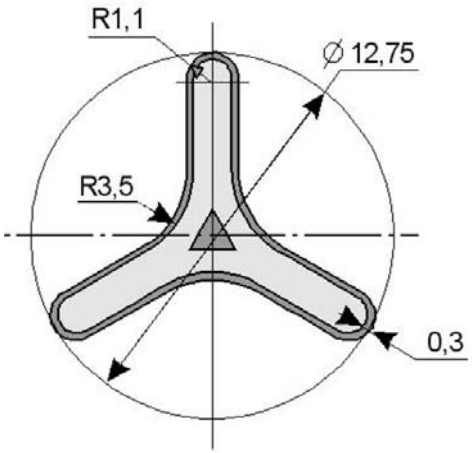
Figure 1 : An artistic representation of the future potential of thorium based nuclear fuels.

- Concept uses a two-part “seed and blanket” concept to tap underappreciated value of thorium
- Burns up weapons-grade plutonium, leaving little residual plutonium

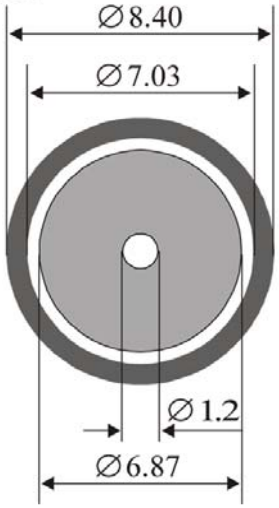
RTPI Seed-Blanket Unit Consists of Pu-Zr Inner Seed and Outer (U,Th)O2 Blanket



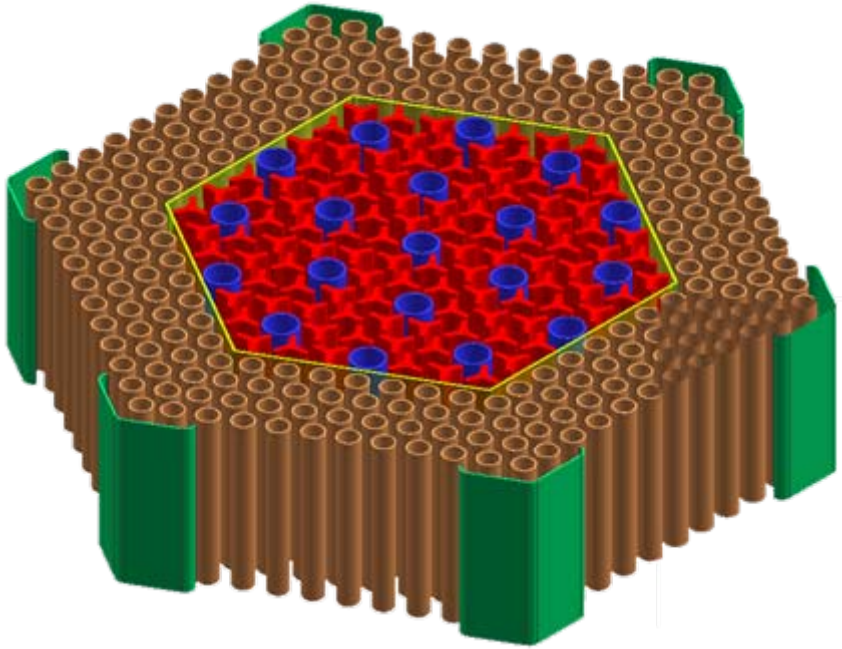
Demonstration mockup of SBU



Seed rod



Blanket rod



- Inner Seed: 108 twisted trefoil rods 10% Pu-Zr alloy
- Outer Blanket: 228 UO2-ThO2 fuel rods (20% enriched uranium)

RTPI, after extensive review, determined to be mostly unsubstantiated hype

- *Key to concept is use of Russian technology for co-extruded metal alloy fuel in seed region*
- Similar co-extruded U-Zr fuel currently used in Russian propulsion reactors (KLT-40S), but with far simpler geometry
- No experience with proposed Pu-Zr alloy, neither production nor irradiation
- Very limited attempts to co-extrude complex twisted trefoil geometry with simulators and U-Zr, but not at required 3-4 m length
- U-Zr and Pu-Zr have distinctly different phase diagrams in temperature and mass contents of interest to RTPI concept (affects extrusion and irradiation performance)
- No benefit found in retaining namesake thorium blanket

Zirconium Cladding of Uranium and Uranium Alloys by Coextrusion*

By A. R. KAUFMANN,† J. L. KLEIN, P. LOEWENSTEIN, AND H. F. SAWYER
Nuclear Metals, Inc.,‡ Cambridge, Mass.

ABSTRACT

The principles governing the techniques used in the coextrusion of two or more metals are discussed in general, and the application of these principles to the fabrication of zirconium-clad uranium fuel elements having integral zirconium end seals is discussed in detail. The extrusion billet consists of a uranium or uranium alloy core surrounded by a zirconium or Zircaloy-2 sleeve and end pieces (cladding); the core and cladding components are enclosed in an evacuated, sealed copper can and extruded. Special precautions to obtain good bonds between core and cladding, uniform cladding, and satisfactory interfaces between core and end seals are described. Specific techniques, component design, billet design, extrusion conditions, and a description of the resultant product obtained (clad rod or tube) are given for the zirconium or Zircaloy-2 cladding of unalloyed uranium, uranium—2 per cent zirconium, uranium—10 per cent molybdenum, uranium—4 per cent silicon, and uranium—5 per cent zirconium—1.5 per cent niobium.

Underlying technology originated not in Russia, but within USAEC

- U-alloys co-extruded with zirconium-alloy cladding were investigated by USAEC and their subcontractors in 1950s and 1960s.
- U-alloy extrusion under conditions of superplasticity for fuel applications was essentially forgotten in the U.S., but utilized in Russia for propulsion reactors such as KLT-40S (icebreaker fleet, floating power plants)
- U.S. backers of RTPI concept were completely unaware of domestic history and promoted U-Zr extrusion technology as unique to Russia
- Reviewers found this only through deep mining of open-source archives

A second example of hype over substance is "standard" ThO2 fuel

- Thorium fertile, but not fissile, so mixed with uranium oxide, either homogeneously or heterogeneously
- Bred U-233 usually burned in-situ
- Shippingport light-water breeder reactor demonstration tested this type of ThO2 fuel extensively
- ThO2 fuel has been tested since by many organizations independently
- Generally good performance, but
  - Difficult (and expensive) to fabricate
  - Difficult to reprocess (and thus also to recycle dirty scrap)

Thorium Energy Independence and Security Act of 2009 (introduced bill, but not passed)

- Promotes use of thorium fuel on basis of energy independence
- Promoted by owner of mineral rights (Thorium Energy, not related to RTPI's Thorium Power)
- Their focused lobbying led to multiple introductions of this bill over past few years, which calls for $250M funding ($50M/yr over five years)
- Intended to support development of domestic thorium fuel cycle including mining of thorium deposits in Lemhi Pass, Idaho

Apparently unknown to promoters, <5 years ago, U.S. government buried its thorium stockpile at NTS

- More than 7M lbs thorium buried
- No market or use for material could be found

So…Is there anything new under the sun?

Maybe??? But it is just as likely that it has already been tried.

Conclusion

- As for future nuclear fuels, always have
  - an open mind, but
  - healthy skepticism of “next great thing”
- UOX has inertia for many reasons
  - It works well enough
  - It is relatively inexpensive
- If someone pushes next great thing, do some digging – it probably has already been tried
- Most of the “next great thing” ideas have scientific merit and are very interesting from research perspective, but

Conclusion (cont.)

- It takes a long time and a lot of money to go from a concept to a proven fuel qualified for use in a commercial power reactor
- Broad knowledge of what has been tried and what has been proposed can be really beneficial,
  - not only to short-circuit proposals that have already been tried,
  - but also for cross pollination.