High Density Fuel Development for Research Reactors

P. Lemoine / D. Wachs
CEA France / INL USA

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- Introduction
- UMo fuel Development Status
- Results & Perspectives on Dispersion Fuels
- Monolithic Development Program
- Qualification and Conversion Program
- Conclusions

Introduction

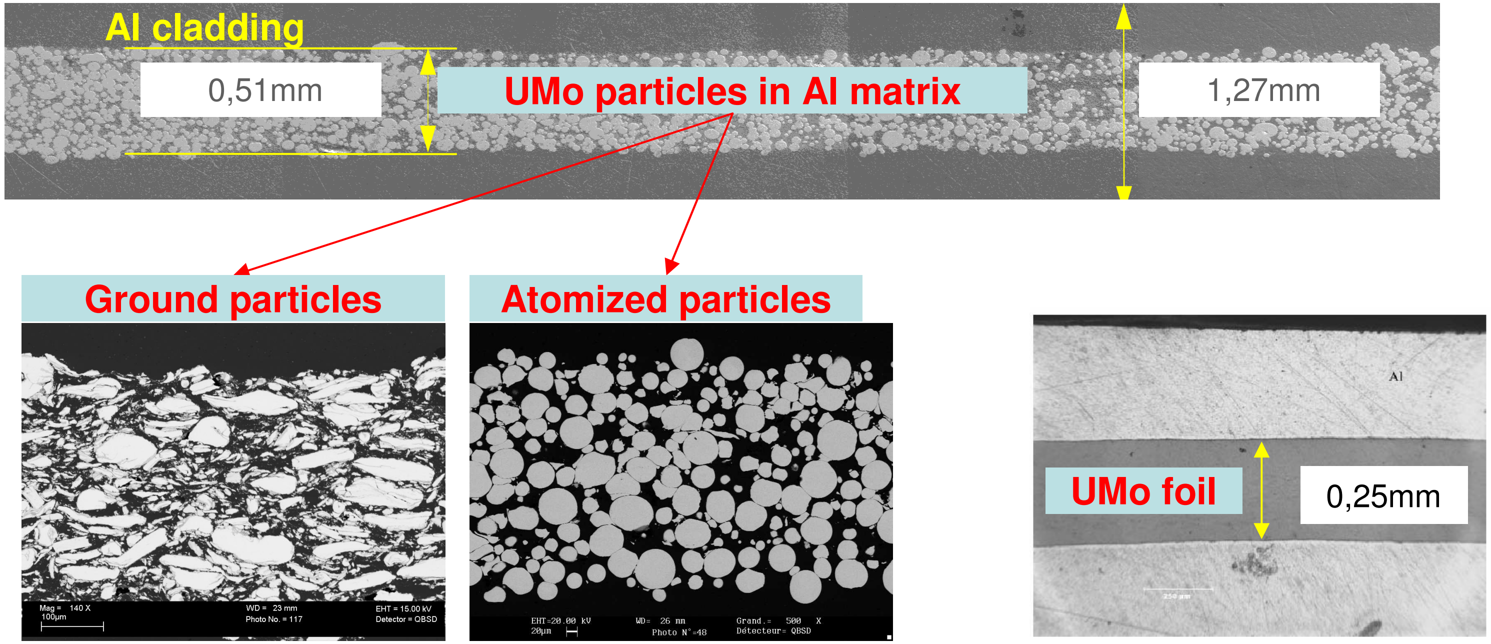
Scope

- **Many Labs are involved in the HD fuel development for RR**
  - CNEA in Argentina,
  - AECL in Canada,
  - CEA, AREVA-CERCA in France,
  - KAERI in Korea,
  - TUM in Germany,
  - VNIIM, RDIPE, INM, IPPE, NCCP, RIAR in Russia,
  - ANL, INL, BWX-T, Y-12 in USA

- **Frequent exchanges are organized between Labs members**
  - At least two times each year (RERTR & RRFM meetings)

- **This presentation is mainly focused on US & French Programs**

High density fuels for RR



Dispersion Fuels (U loading 8gU/cm^3)

Monolithic fuel (16gU/cm^3)

Why UMo alloys?

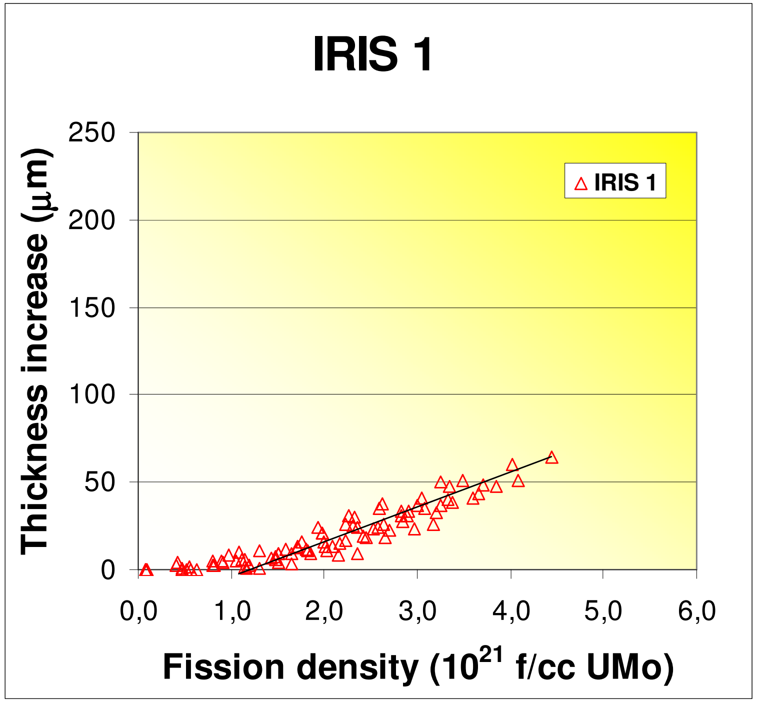
Compound or alloy	UAl_2	U_3Si_2	U_6Fe	U_6Mn	U	U-7%Mo alloy	U-9%Mo alloy
Density	8.1	12.2	17.7	17.8	19.0	17.4	17.0
U-loading (1) (g/cm^3)	3.3	5.8	8.5	8.5	9.5	8.2 16.4 (2)	7.8 15.6 (2)
	Too low density limits		Too poor irradiation behavior			Best candidates for HD fuels	

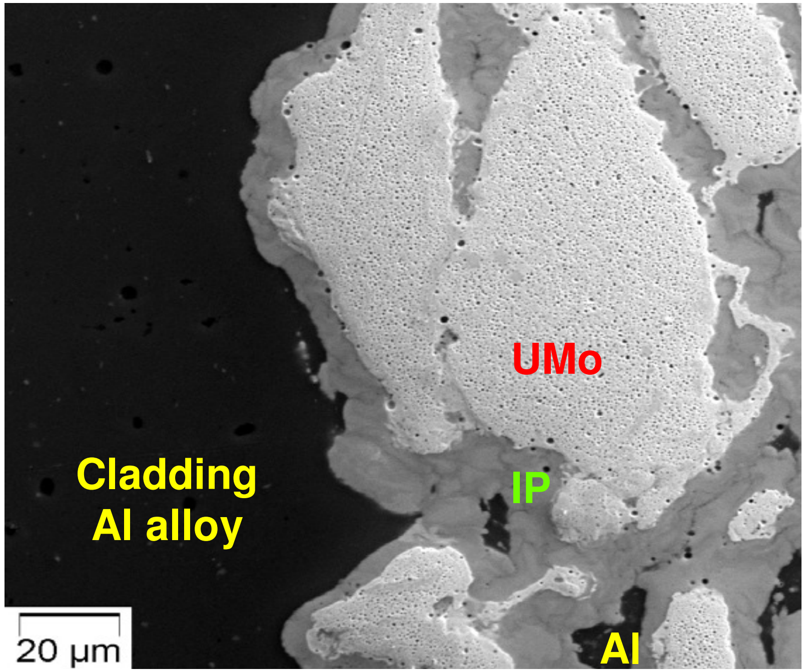
(1) Assuming a 50% volume fraction of particles ; (2) For monolithic form

UMo Fuel development Status

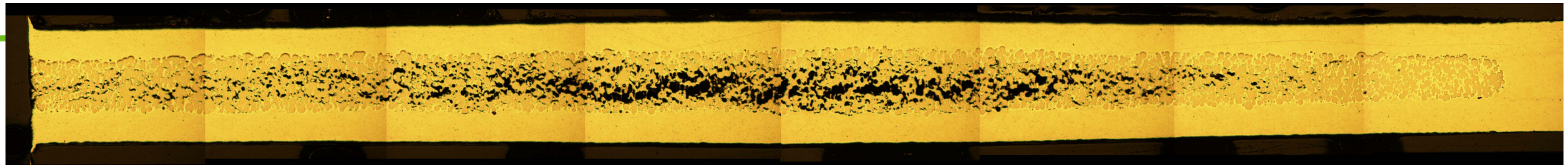
Early Test Results (1997-2002)

- Early in-pile tests (RERTR 1, 2, 3 ; IRIS-1) have proved:
  - The **good in-pile behavior of UMo particles** (low, stable swelling)
  - An **interaction between UMo particles and Al matrix more sensitive to the temperature** than anticipated



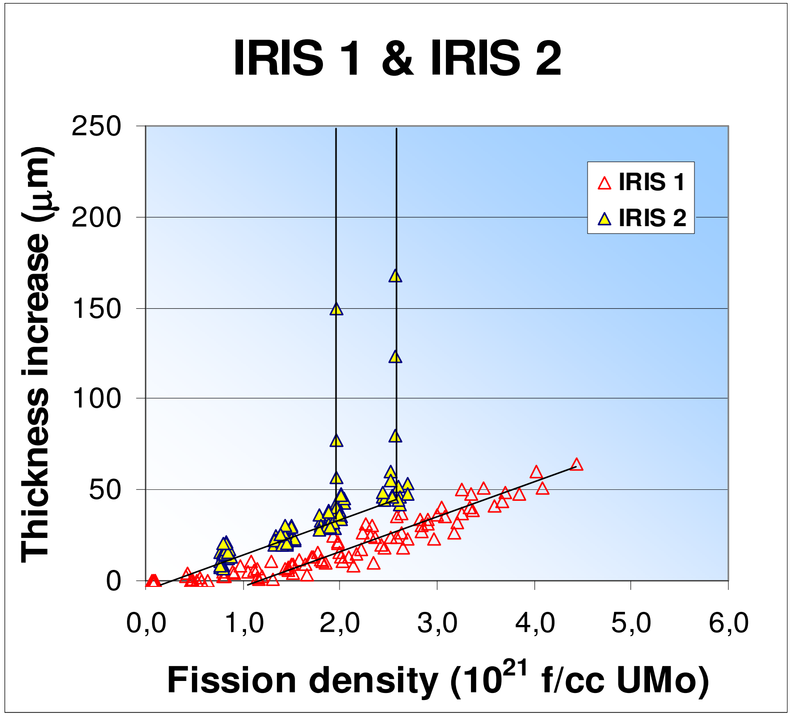


Performance Limitations (1/3)



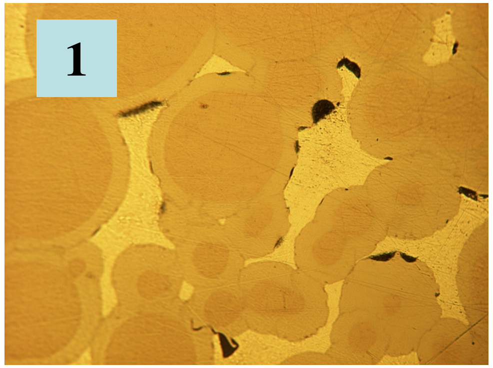
- **"UMo/Al Plate pillowing"**:
  - **Was firstly discovered during "FUTURE" test at low burn-up**
  - **Was confirmed during many other tests as IRIS-2, RERTR-4, Russian tube, … at low or higher burn-up**

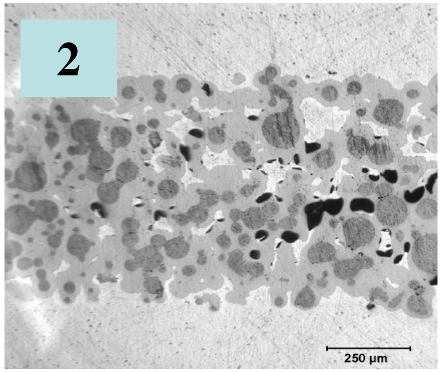
- **Plate is locally affected by a sharp thickness increase (~few 100µm)**
- **Origin and appearance conditions are now well understood**

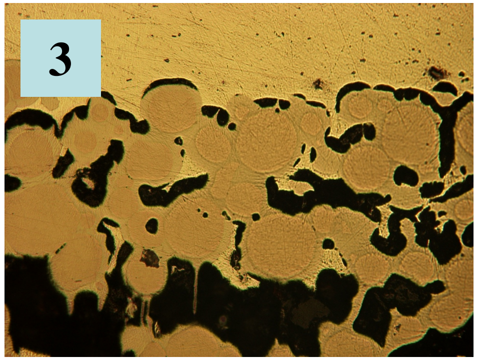


UMo/Al Performance Limitations (2/3)

- **The main reasons of "plate pillowing" are:**
  - an **excessive formation of Interaction Phase** (IP)
  - the inability of this compound to retain fission gas in the form of stable bubbles due to its **amorphous structure** [1]
- **This poor fission gas retention causes:**
  - the development of pores at the interface IP/Al matrix **(1),**
  - leading to plate pillowing (3) by growth and pores connection (2)



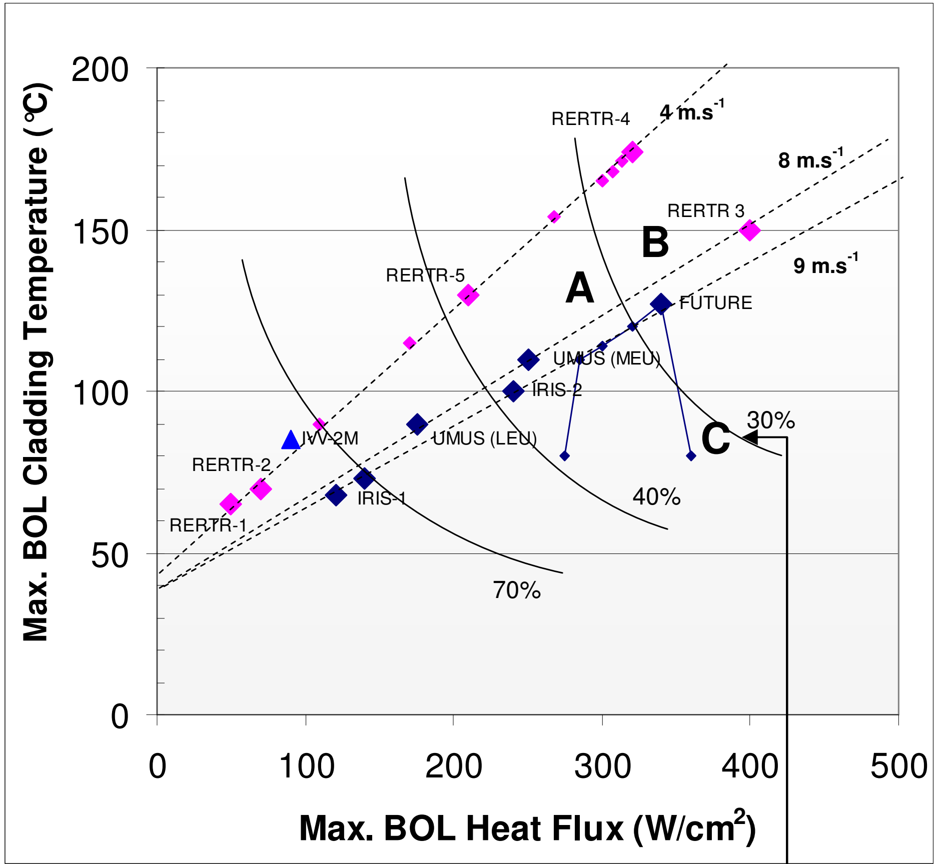


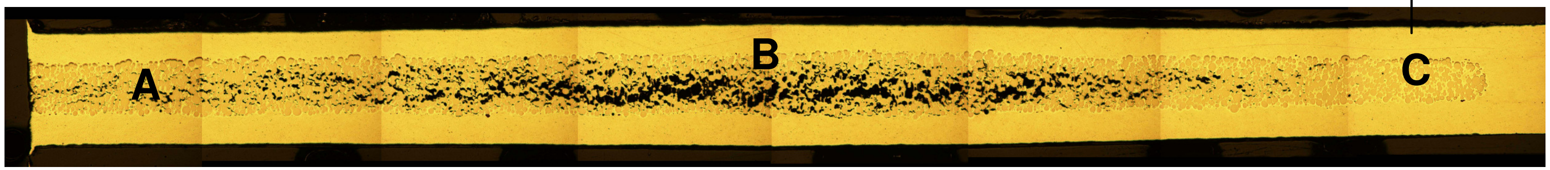


- [1] **Note:**
  - **The amorphous character of the IP, firstly suggested par G. Hofman (ANL), has been recently proved by S. Van den Berghe (SCK-CEN Mol) using TEM analysis, and O. Golosov (INM) using SANS (Prague 2007)**

UMo/Al Performance Limitations (3/3)

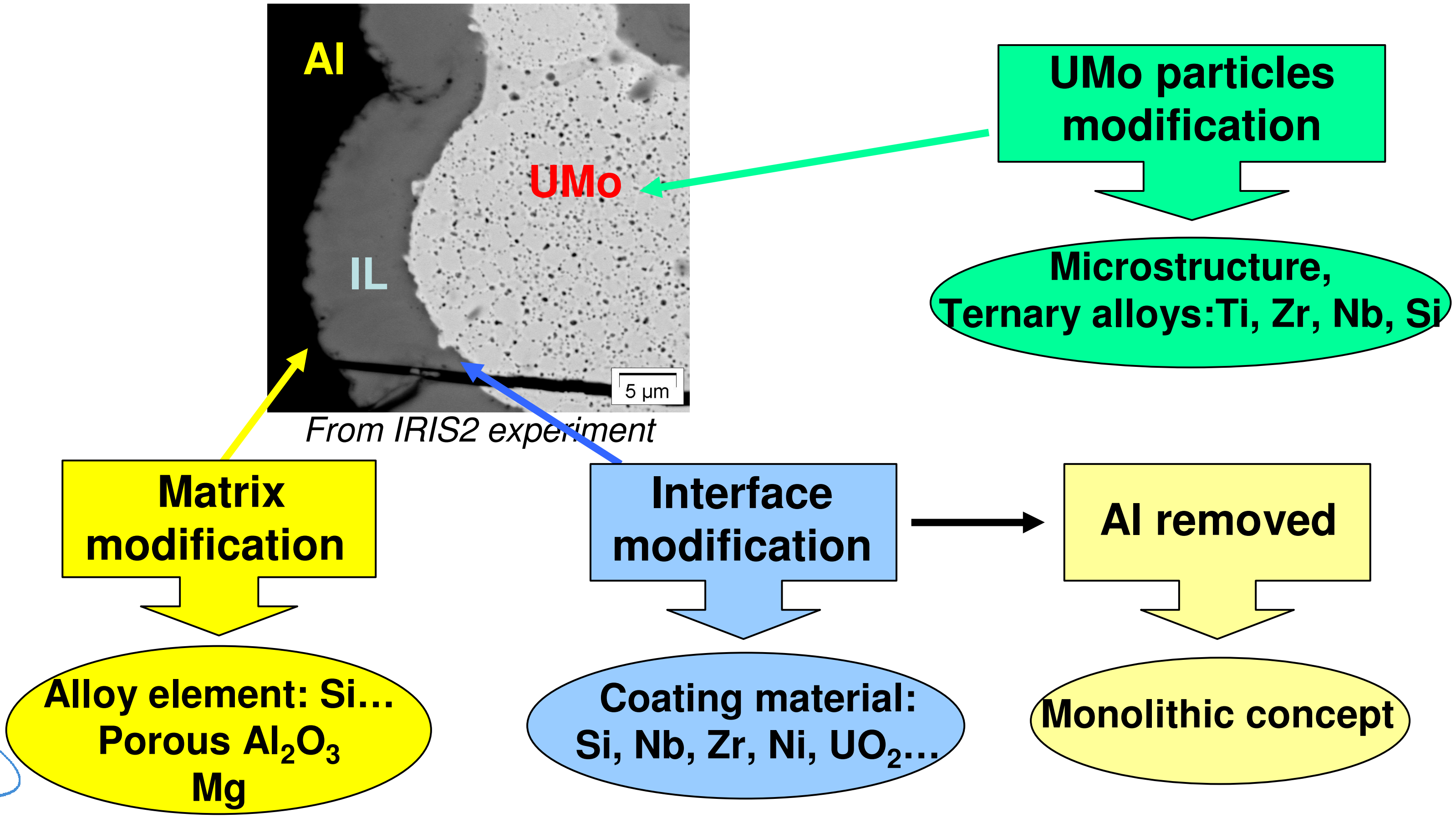
- **Differences in behavior from test to test have been explained by the combination of the test conditions (fission rate, burn-up, temperature) more or less critical.**





Ways of improvement

- To improve the UMo/Al concept and its using at medium and high power operating conditions, different approaches have been proposed and are currently investigating

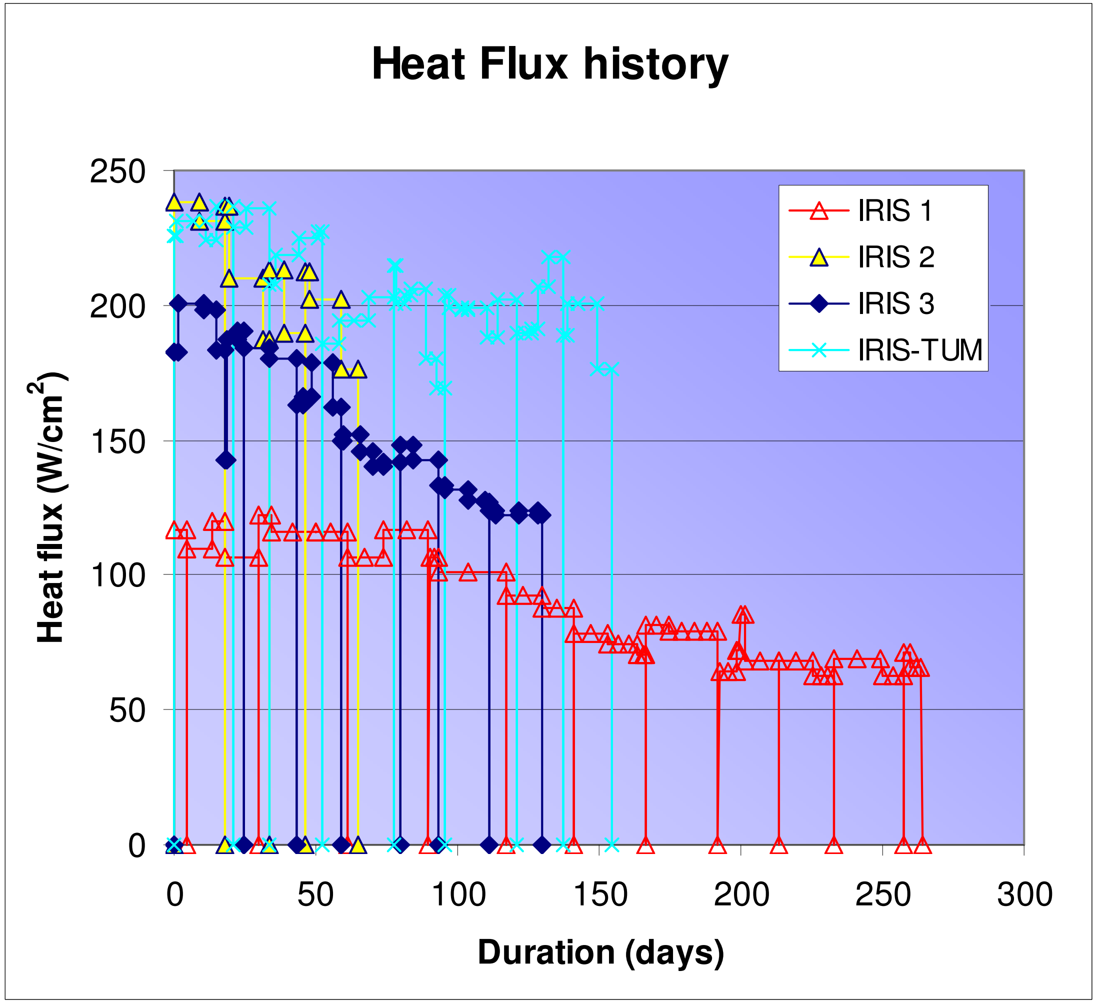


Results & Perspectives on Dispersion Fuels

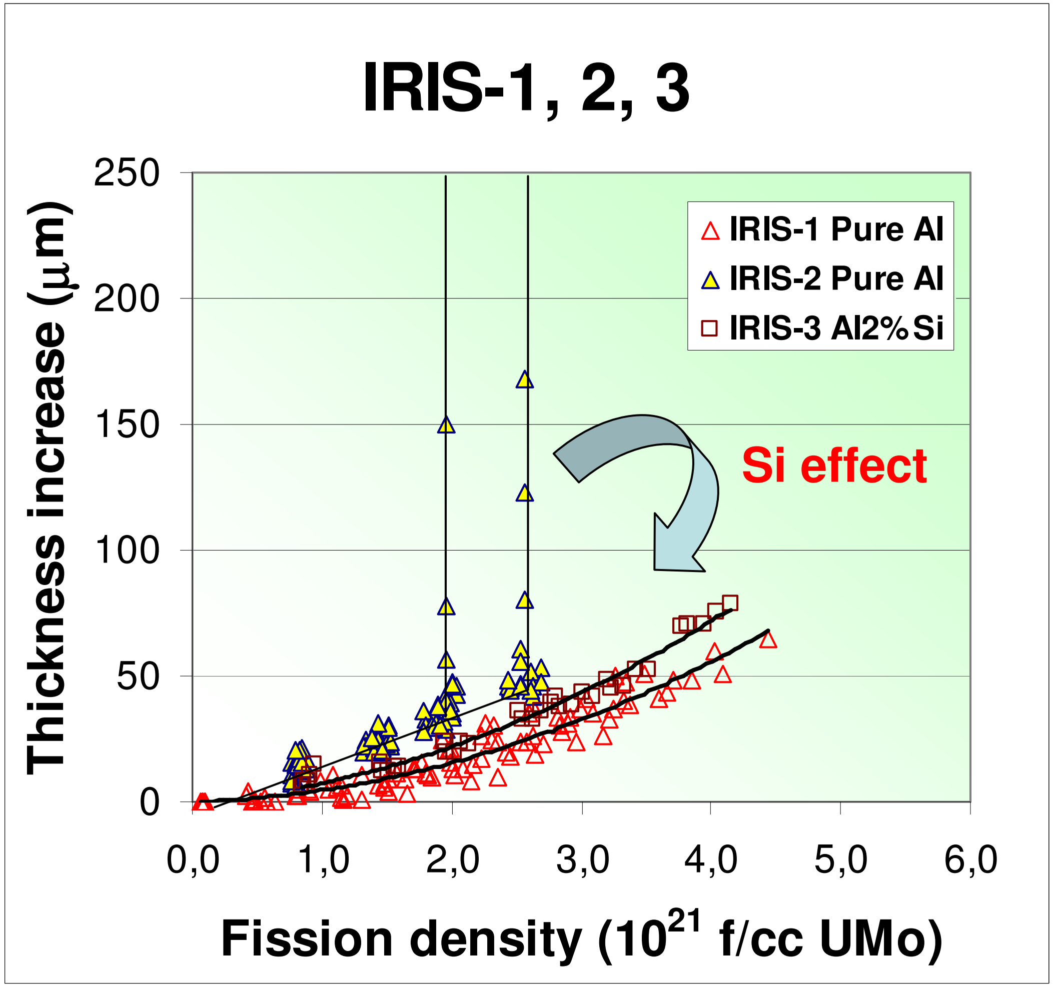
IRIS Program on UMo dispersion full size plates

	Fuel Particles	Matrix Powder	Heat flux (W/cm^2)	Status
IRIS-1	Ground (UMo7&9)	Pure Al	130	Irradiation & PIE completed
IRIS-2	Atomized (UMo7)	Pure Al	240	Irradiation & PIE completed
IRIS-3	Atomized (UMo7)	Al+0.3%Si Al+2.1%Si	200	Irradiation completed PIE in progress
IRIS-TUM	Ground (UMo9 e50%)	Pure Al Al+2.1%Si	240	Irradiation completed PIE in progress
IRIS-4	Atomized & Oxidized	Pure Al Al+2.1%Si	260	Planned in 2008

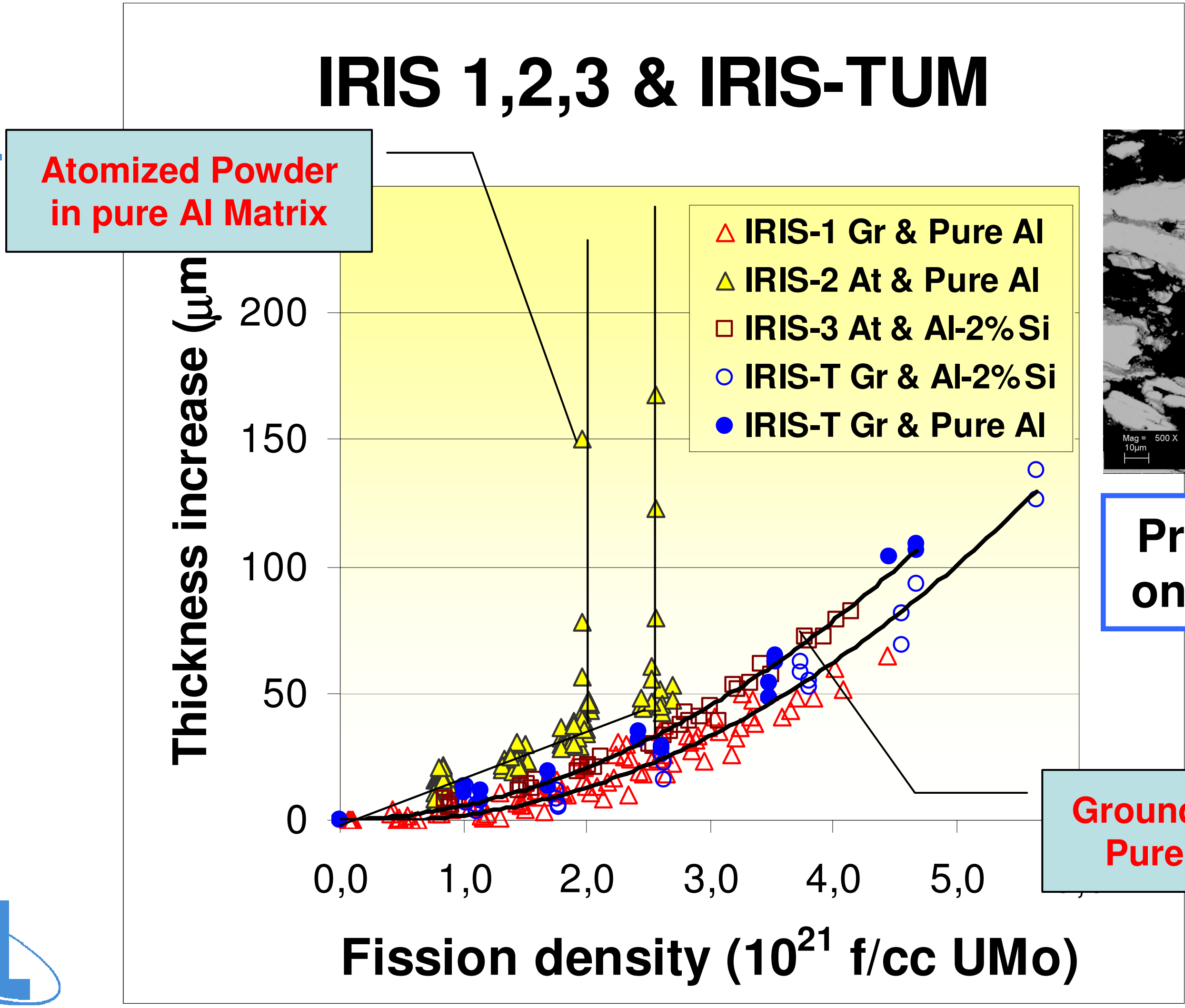
IRIS Program

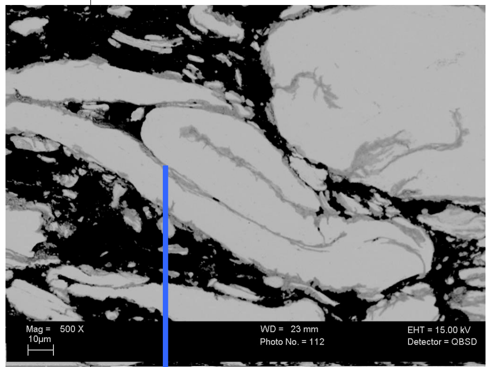


IRIS-3 Results: Silicon additive Effect



IRIS-TUM Results: Ground particles Effect





Presence of oxide on ground powder

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IRIS Program & Perspectives

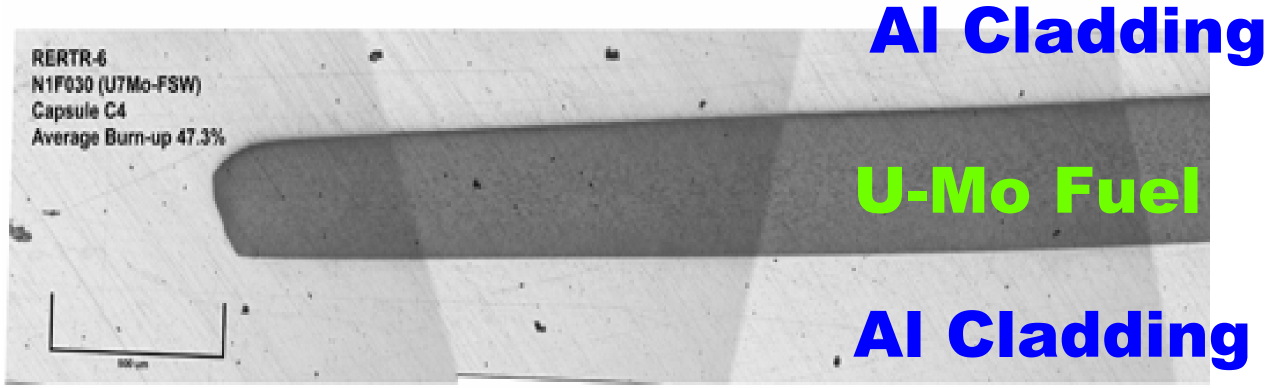
- **Si additive (IRIS-3)**
  - The 2% Si additive in Al matrix have a clear effect on the irradiation behavior of dispersion fuel
  - Silicon is supposed reduce:
    - The growth rate of the Interaction Product (IP)
    - The pore formation at the IP/Matrix interface by increasing its specific surface energy
  - PIE are planned in 2008

- **Oxide coating (IRIS-1/IRIS-TUM)**
  - The better behavior of ground particles than atomized ones, (without Si additive), is attributed to the surface oxidation of the ground particles (acting as an oxide coating)
    - Specific test (IRIS-4) to proved that is planned in 2008 on atomized and pre-oxidized particles

- **Full size Element Qualification**
  - Depending of these tests issue, Qualification Program on full size Fuel Element will be planned in 2010-2011

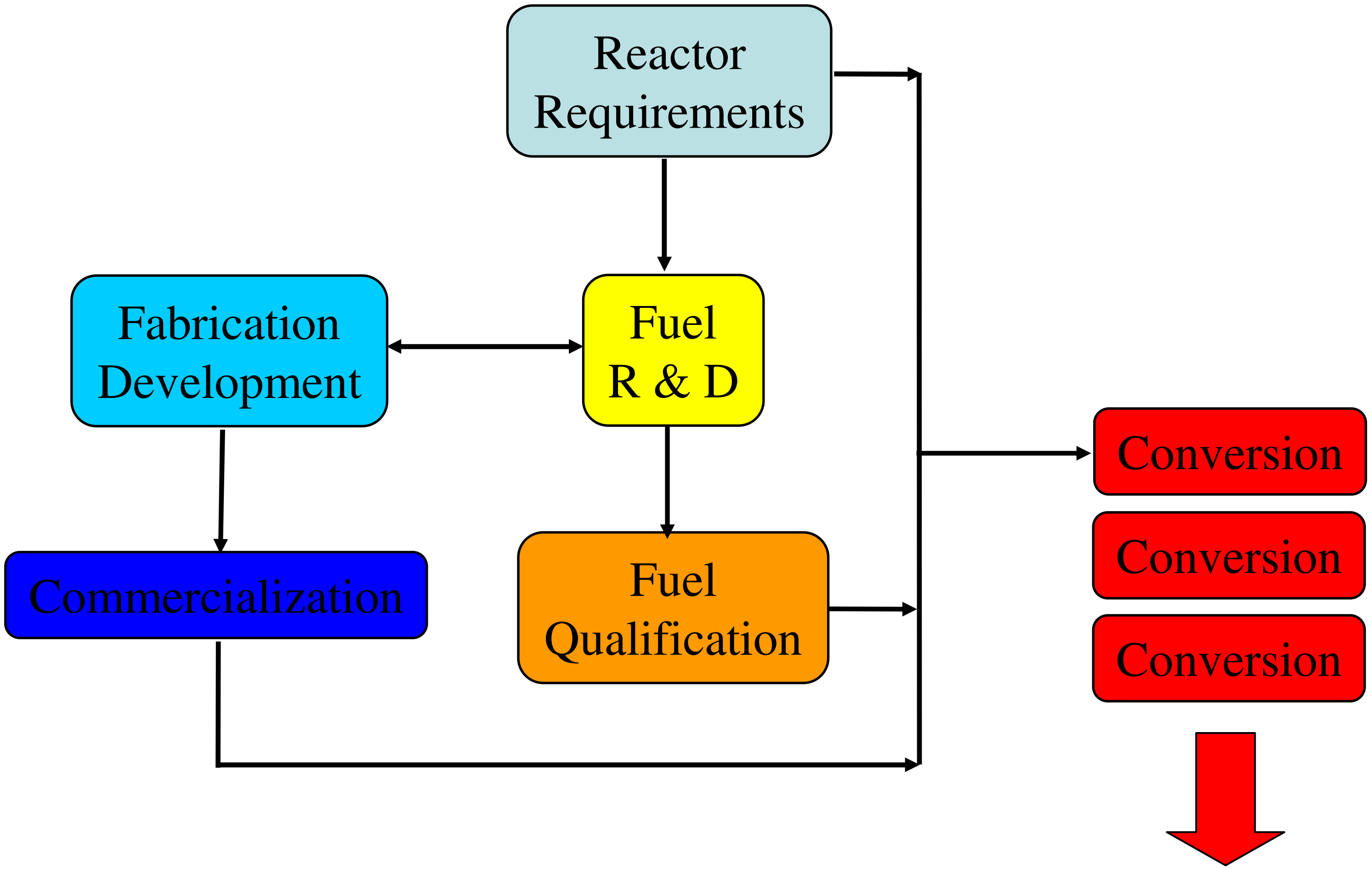
Monolithic Fuel Development

Monolithic Fuel Development



The US program is focusing on monolithic fuel development because 5 of 6 US high performance reactors will require it to support conversion to LEU

Fuel Development and Conversion



Monolithic Fuel Development

- **Fabrication Development**
  - Fabrication of U-Mo foils by rolling
  - Bonding of cladding to fuel
- **Completion of mini-plate irradiation tests (RERTR-6, RERTR-7, and RERTR-8)**
  - Fuel continues to behave very well at very high fission density
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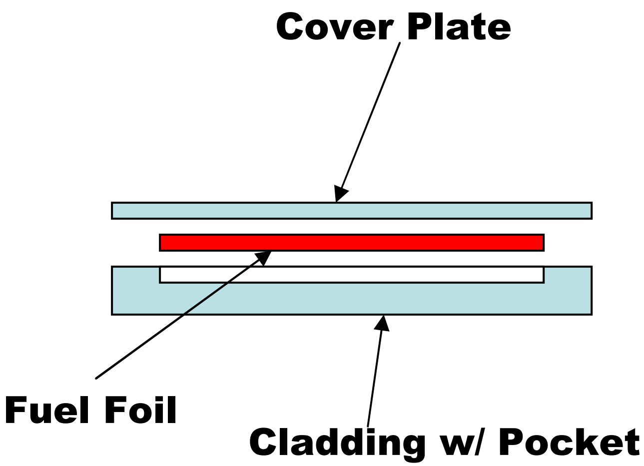
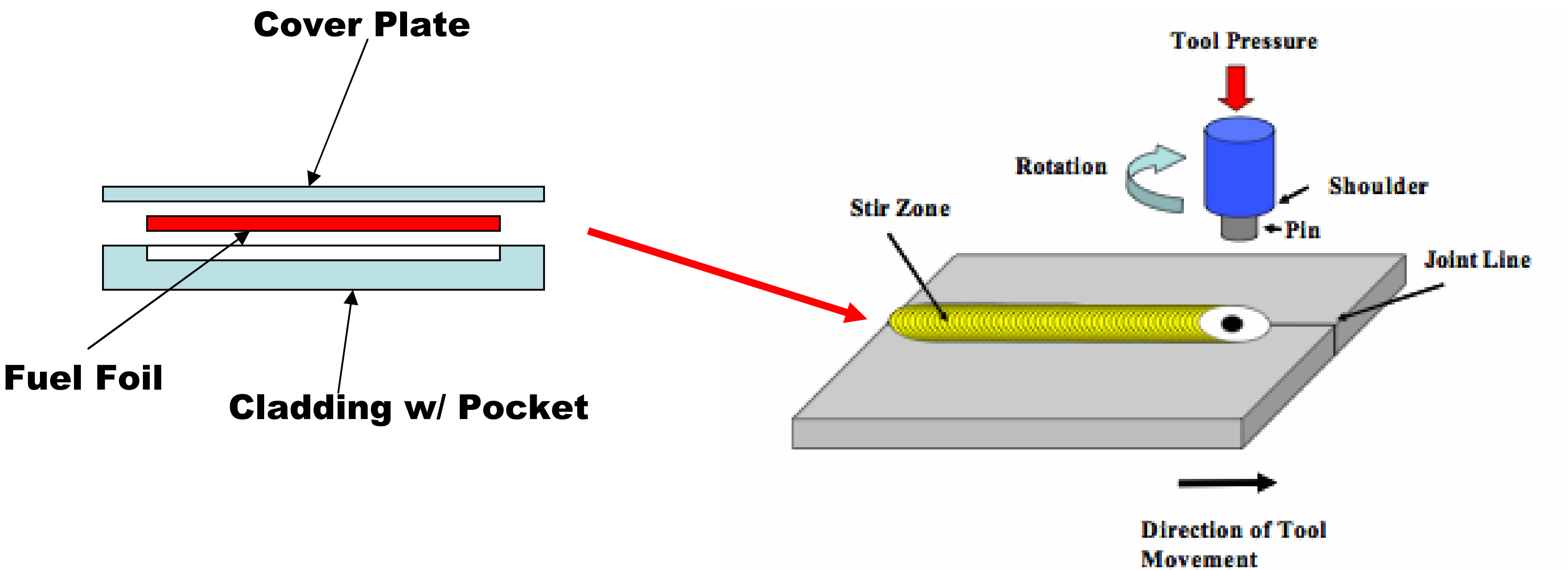
Monolithic Fuel Development

Friction Bonding



Monolithic Fuel Development

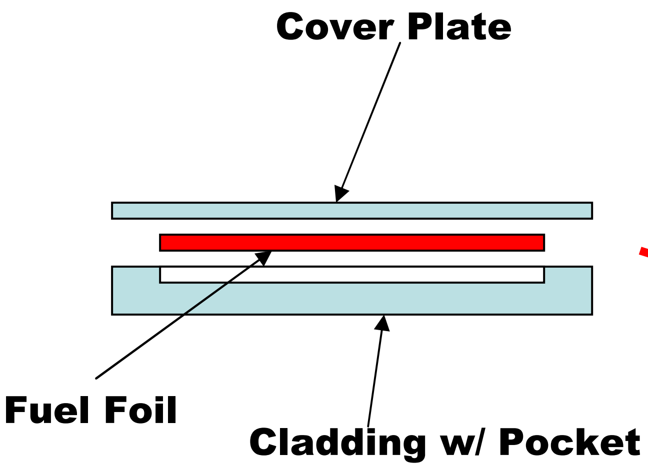
Friction Bonding

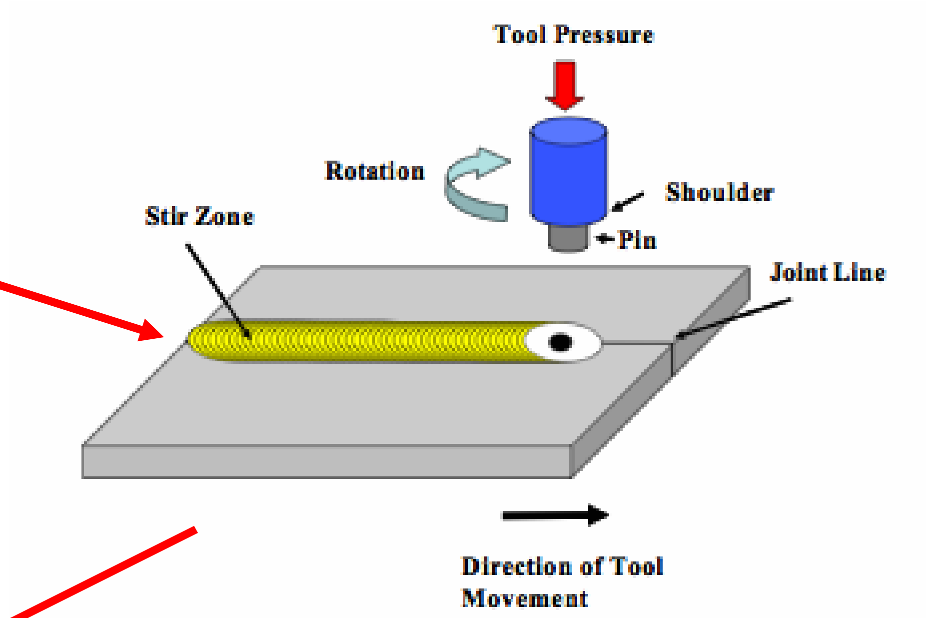


(Bonding process is based on Friction Stir Welding of joints)

Monolithic Fuel Development

Friction Bonding





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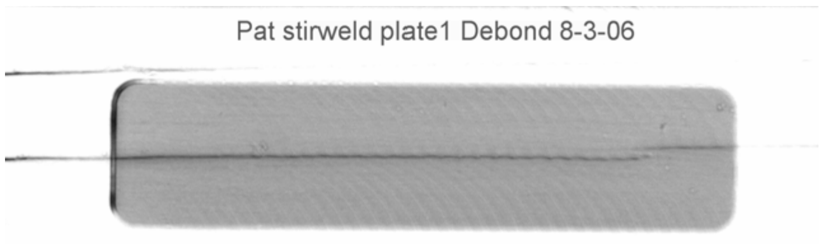
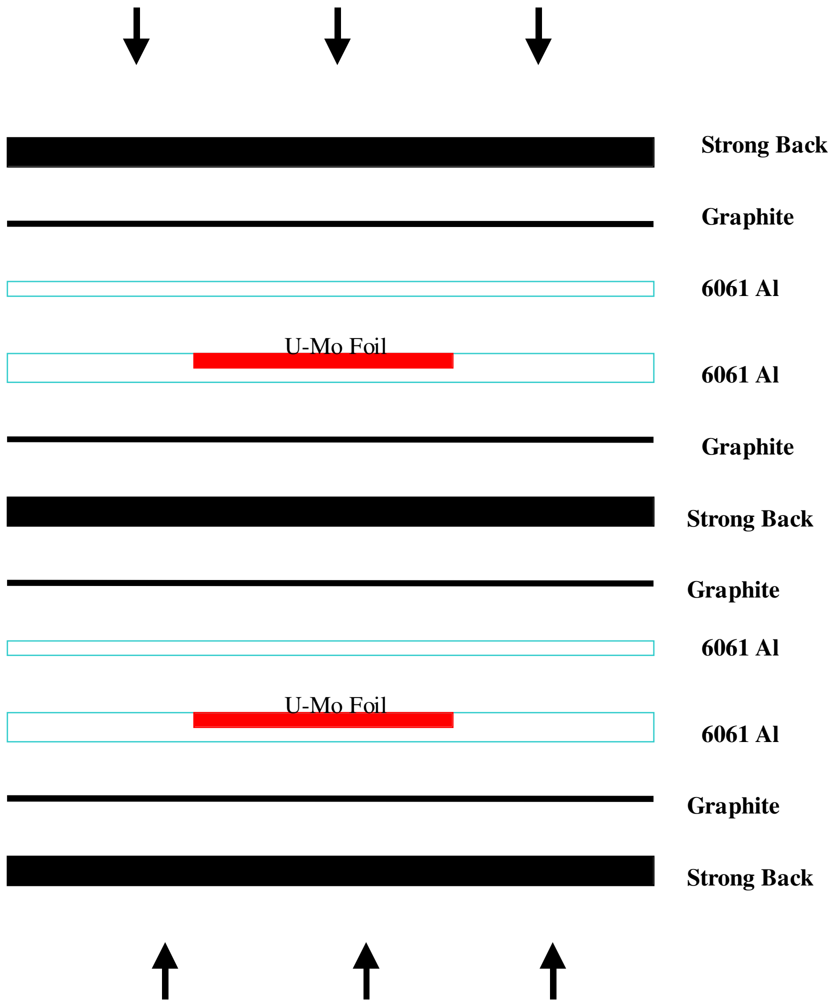


UT Scan of finished plate

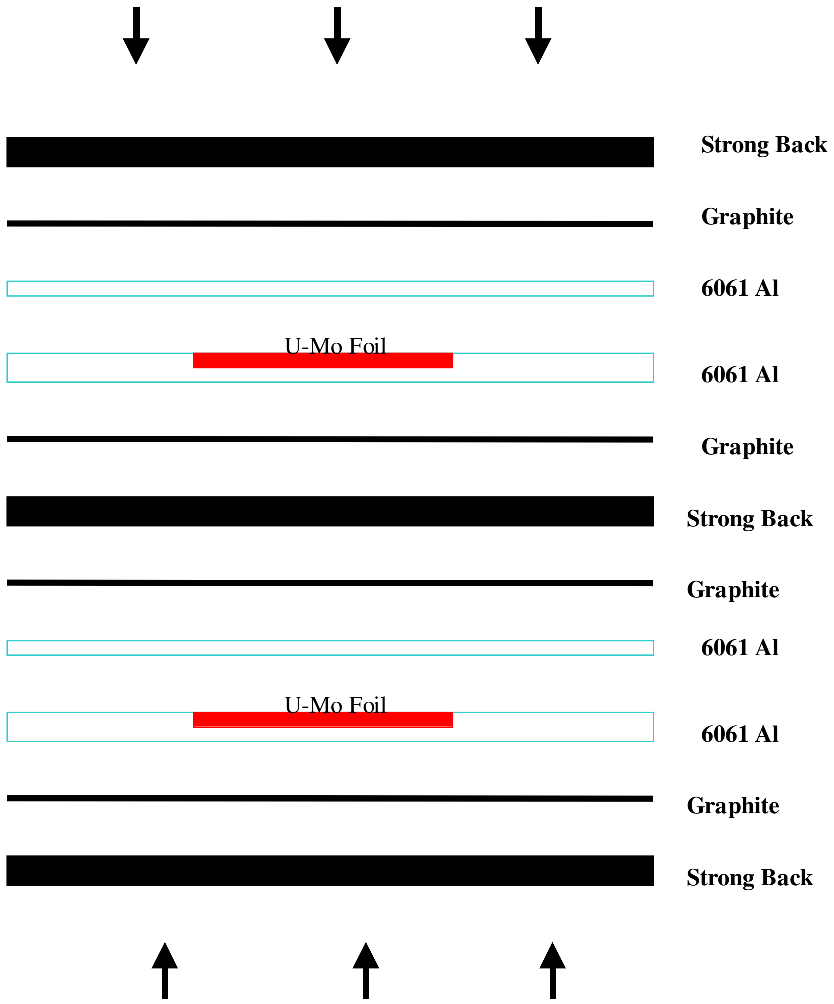
Monolithic Fuel Development

Hot Isostatic Pressing



Monolithic Fuel Development

Hot Isostatic Pressing



Monolithic Fuel Development

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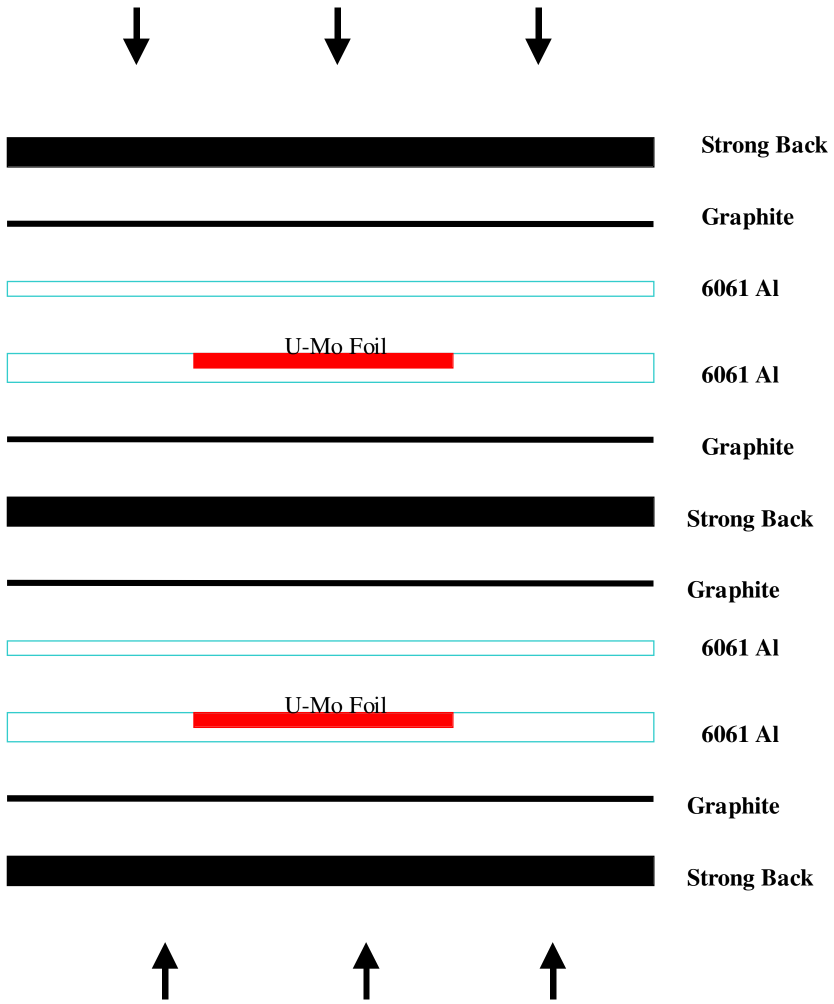
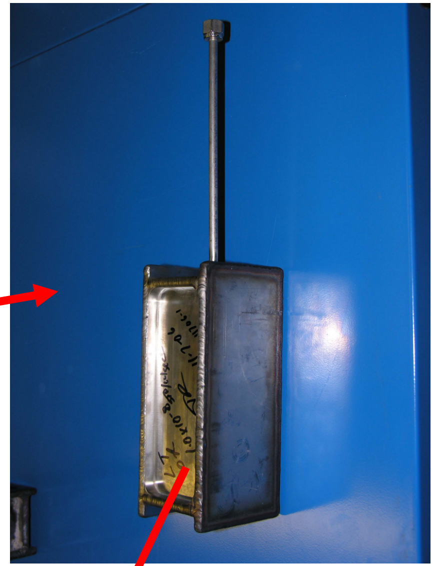




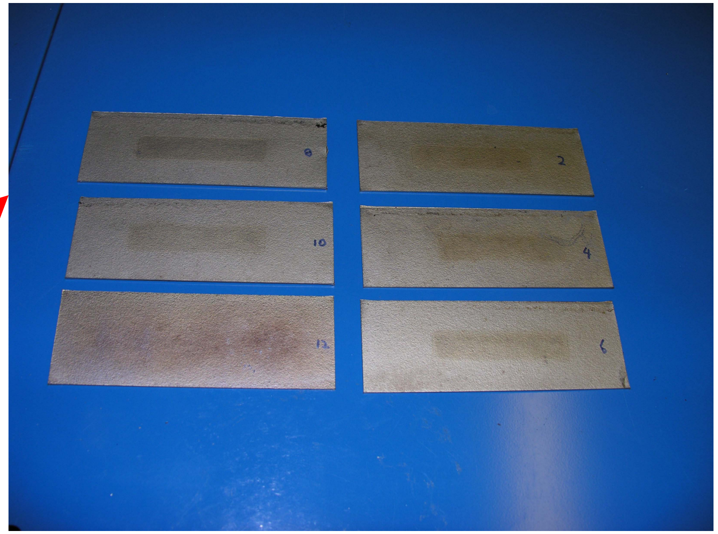
Monolithic Fuel Development

Hot Isostatic Pressing

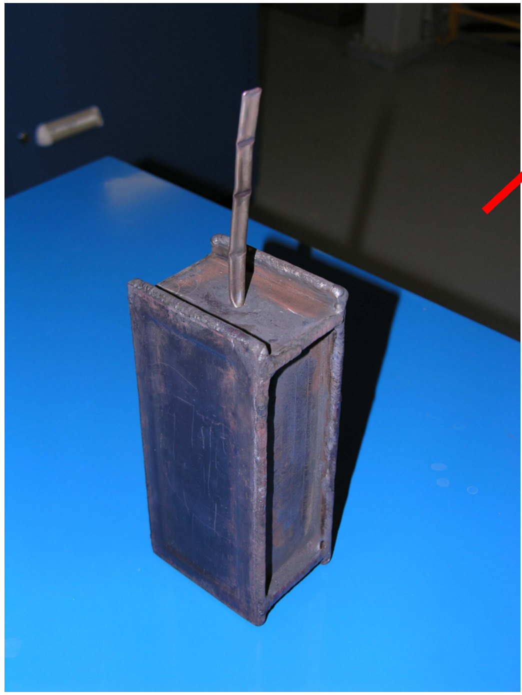
HIP Can

Monolithic Fuel Development

Hot Isostatic Pressing



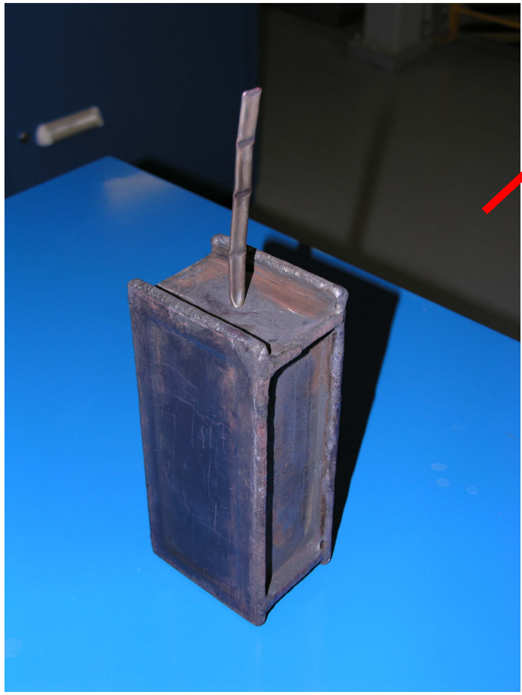
Fuel Plates



HIP Can

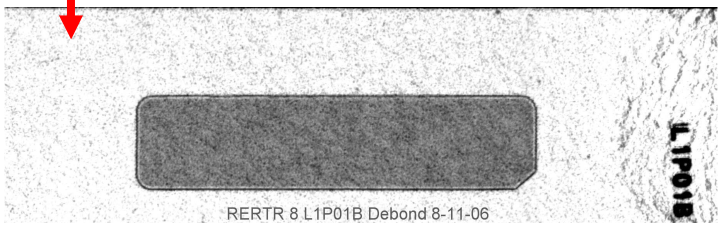
Monolithic Fuel Development

Hot Isostatic Pressing



HIP Can

Fuel Plates



UT Scan of Plate

Monolithic Fuel Development

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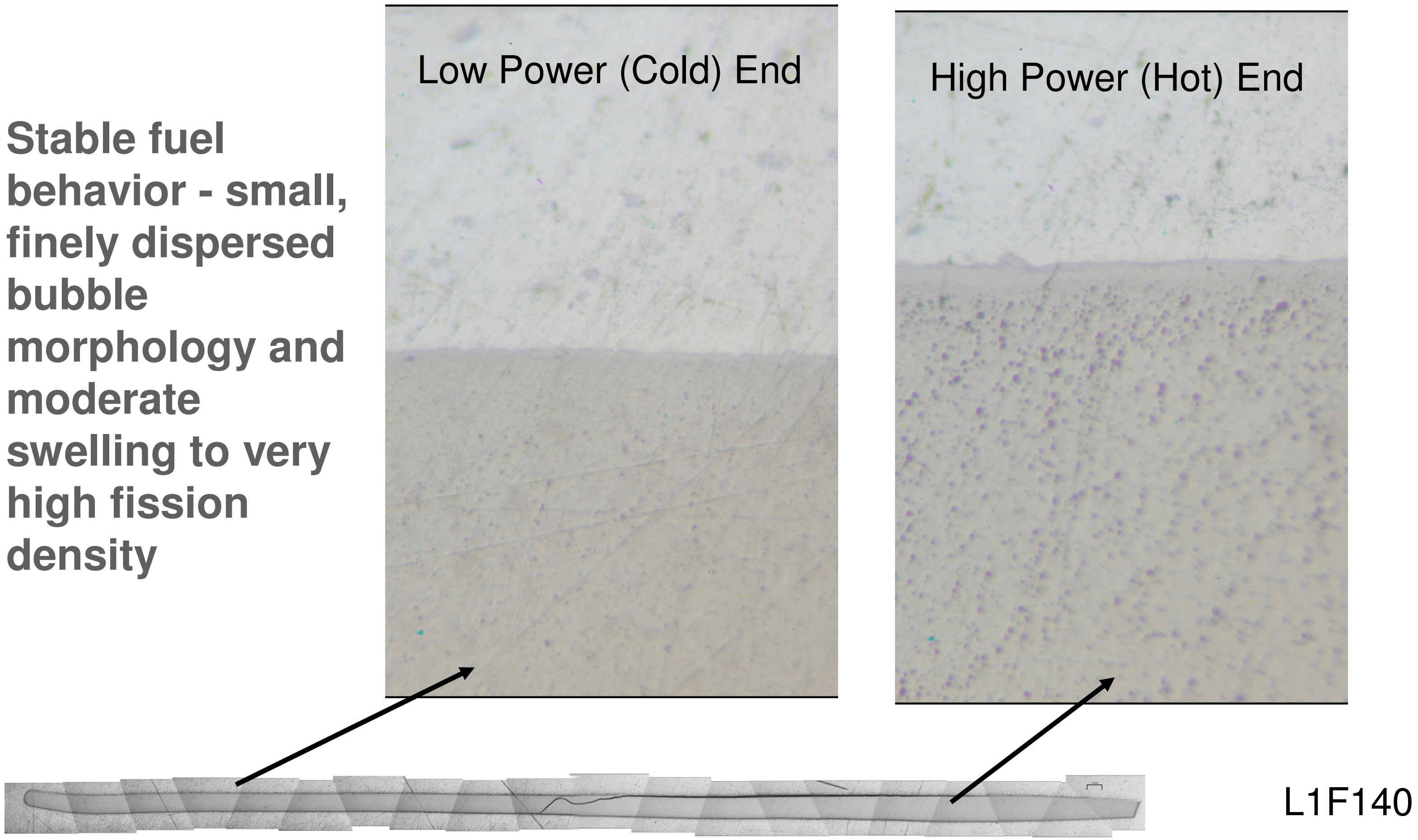
Monolithic Fuel Development

Stable fuel behavior - small, finely dispersed bubble morphology and moderate swelling to very high fission density



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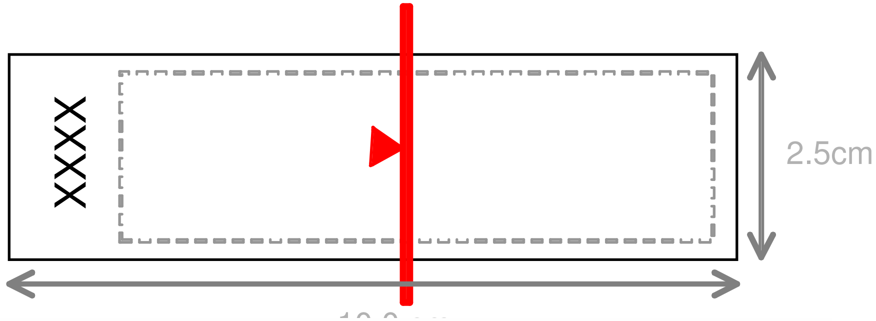
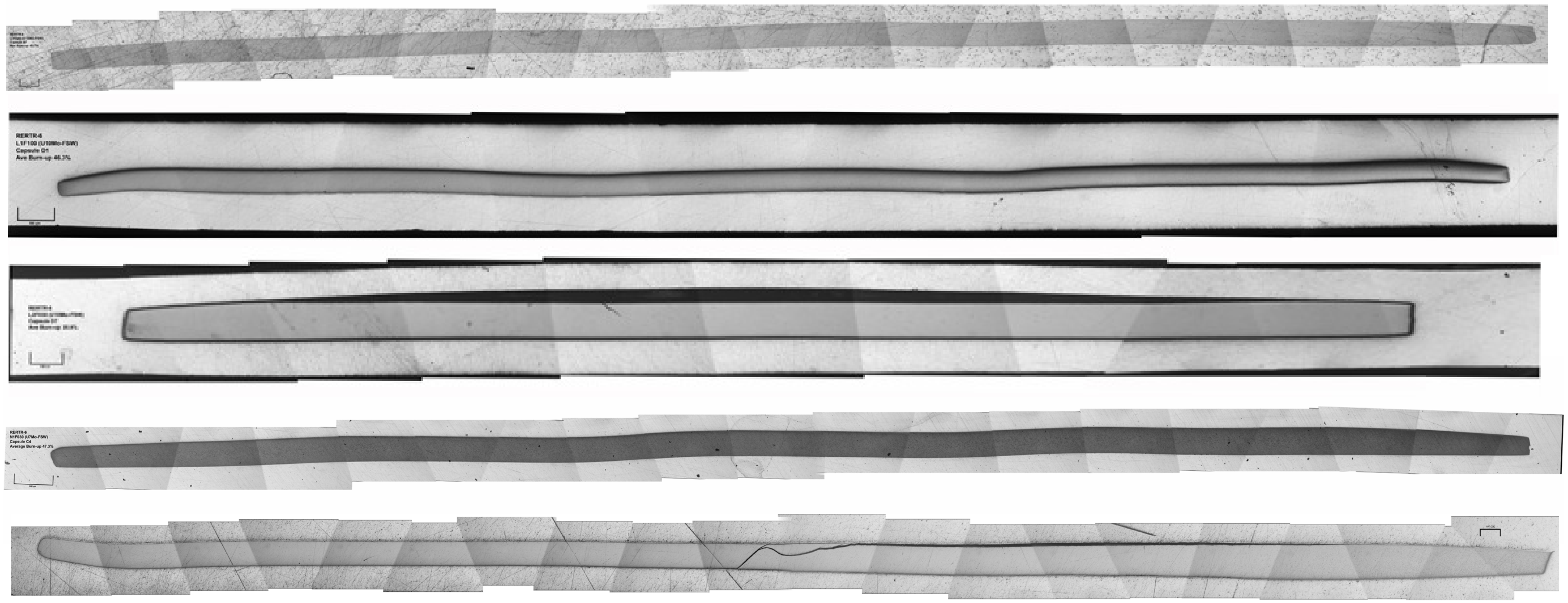
INL

Monolithic Fuel Development

U-xMo alloy (x=7, 10, or 12), Al-6061 cladding, **no interlayer**





LIF040

LIF100

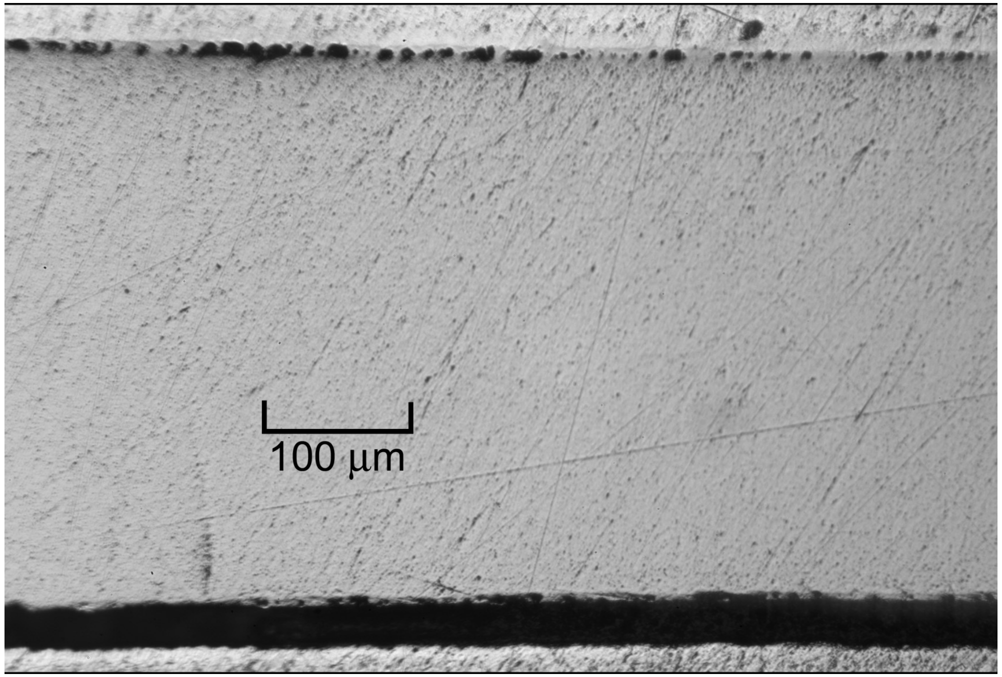
L2F

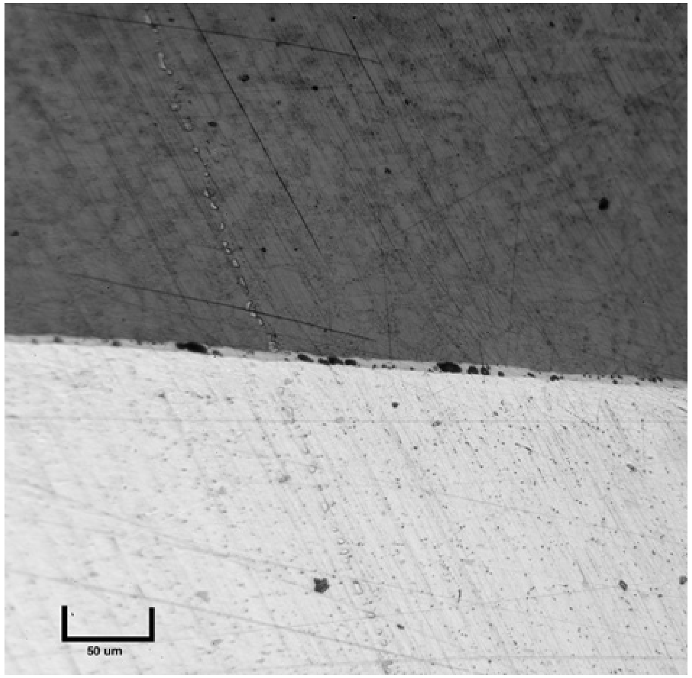
NIF030

LIF140

Monolithic Fuel Development

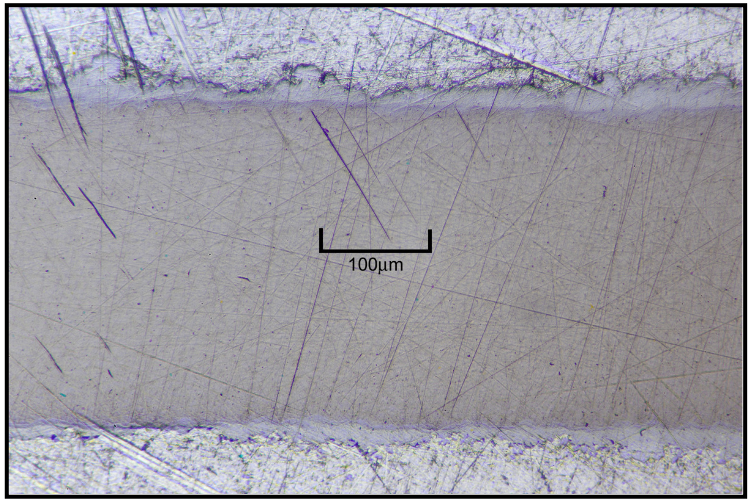
Onset of porosity in fuel/clad interaction layer (higher Mo content more resistant to bubble formation)



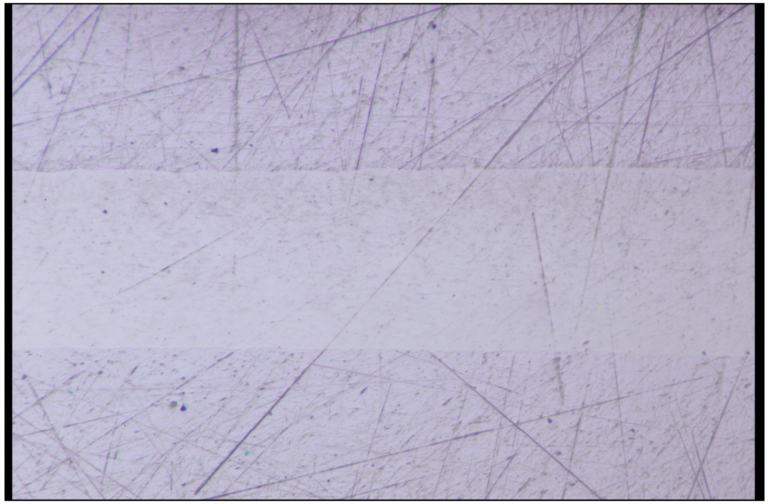


Monolithic Fuel Development

- Silicon rich interlayer between fuel and cladding
- Zirconium diffusion barrier between fuel and cladding



Mini-plate with silicon rich interlayer is stable to high burnup



CNEA supplied plate with zircalloy cladding shows no interaction product formation

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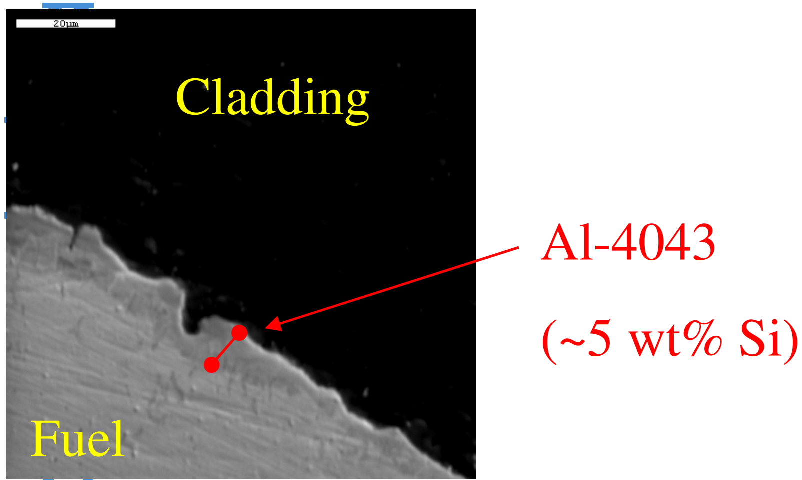
Monolithic Fuel Development

Modified Fuel/Clad Interface for RERTR-9A and -9B Test

As-fabricated interface layers



Al-4043 Interlayer (HIP)

Monolithic Fuel Development

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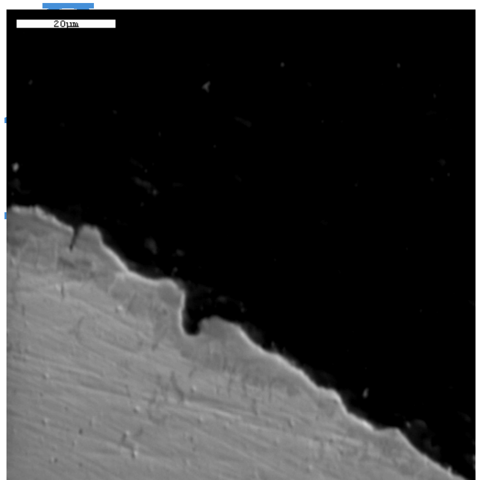

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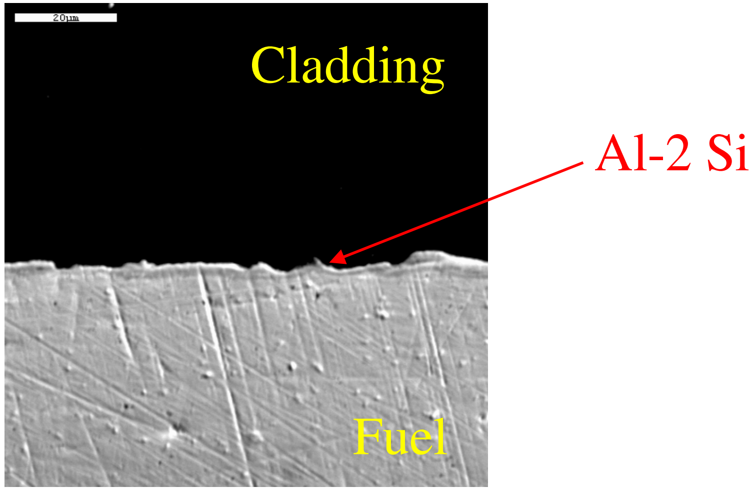

Thermal Spray Al-2Si (HIP & FB)

Monolithic Fuel Development

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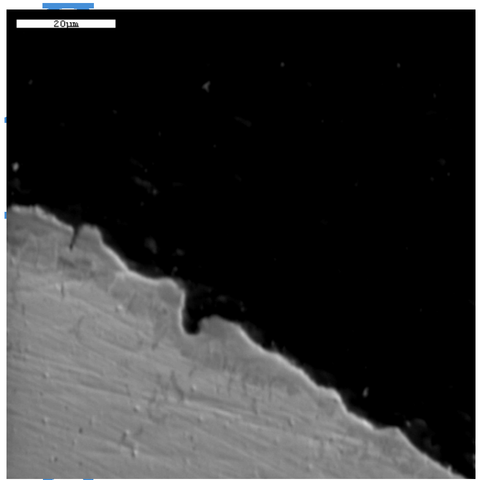

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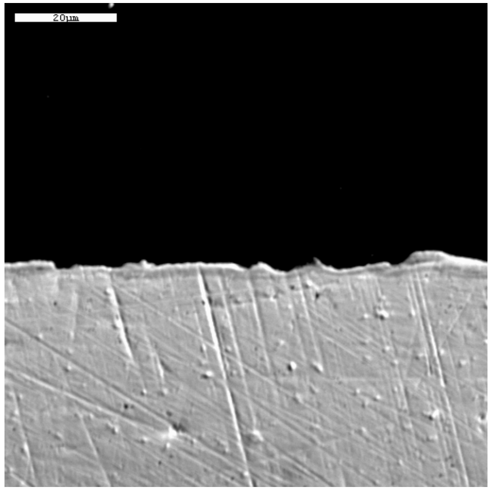

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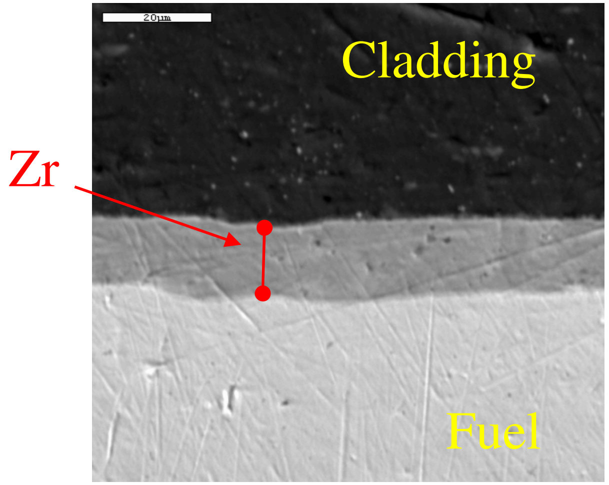

Zr diffusion barrier (HIP & FB)

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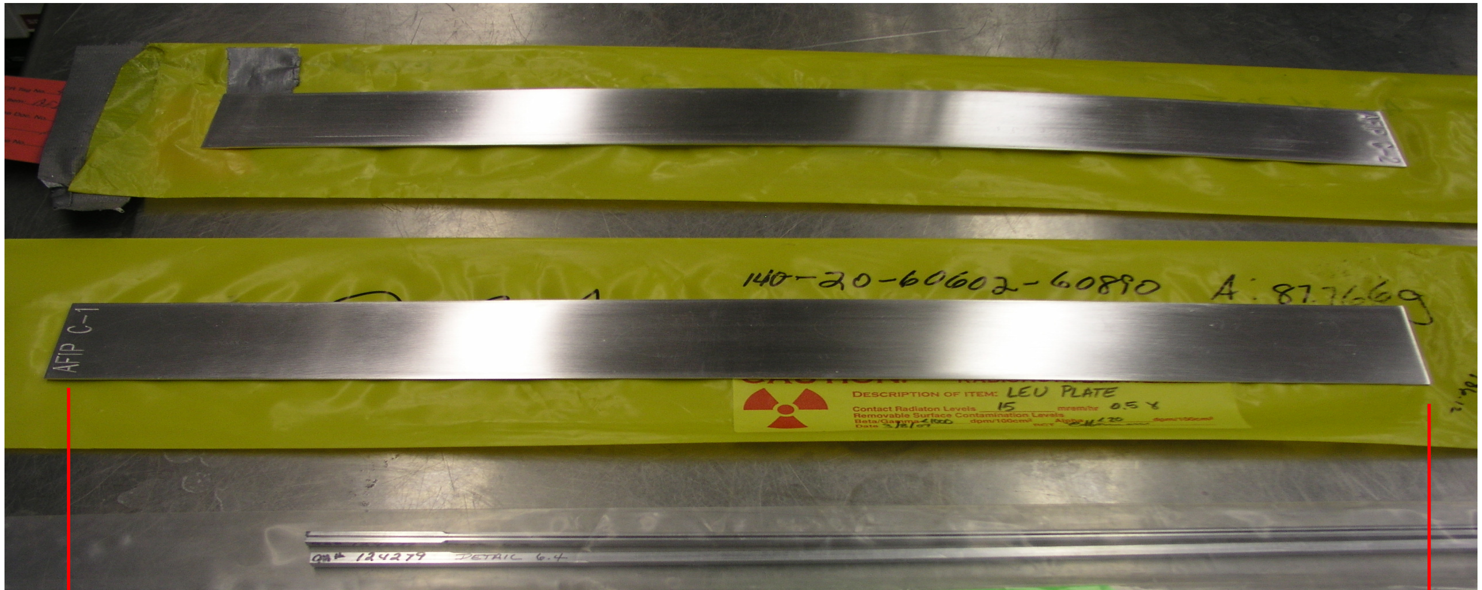
Monolithic Fuel Development

Full-size Fuel Plate Fabrication (by Friction Bonding)



~ 60 cm

Monolithic Fuel Development Plan

- **Fuel development activities will emphasis monolithic fuel form**
  - Demonstration of full size fuel fabrication
  - Fuel/clad interface behavior (chemical and mechanical)
  - Integrated mechanical behavior of fuel
- **Fuel performance demonstration**
  - Irradiation Tests
    - Mini-plates to evaluate chemical and irradiation properties
    - Full-size plates to evaluate integrated mechanical behavior
  - Fuel design downselection planned for end of FY08
  - Fuel qualification report to be submitted by end of FY09

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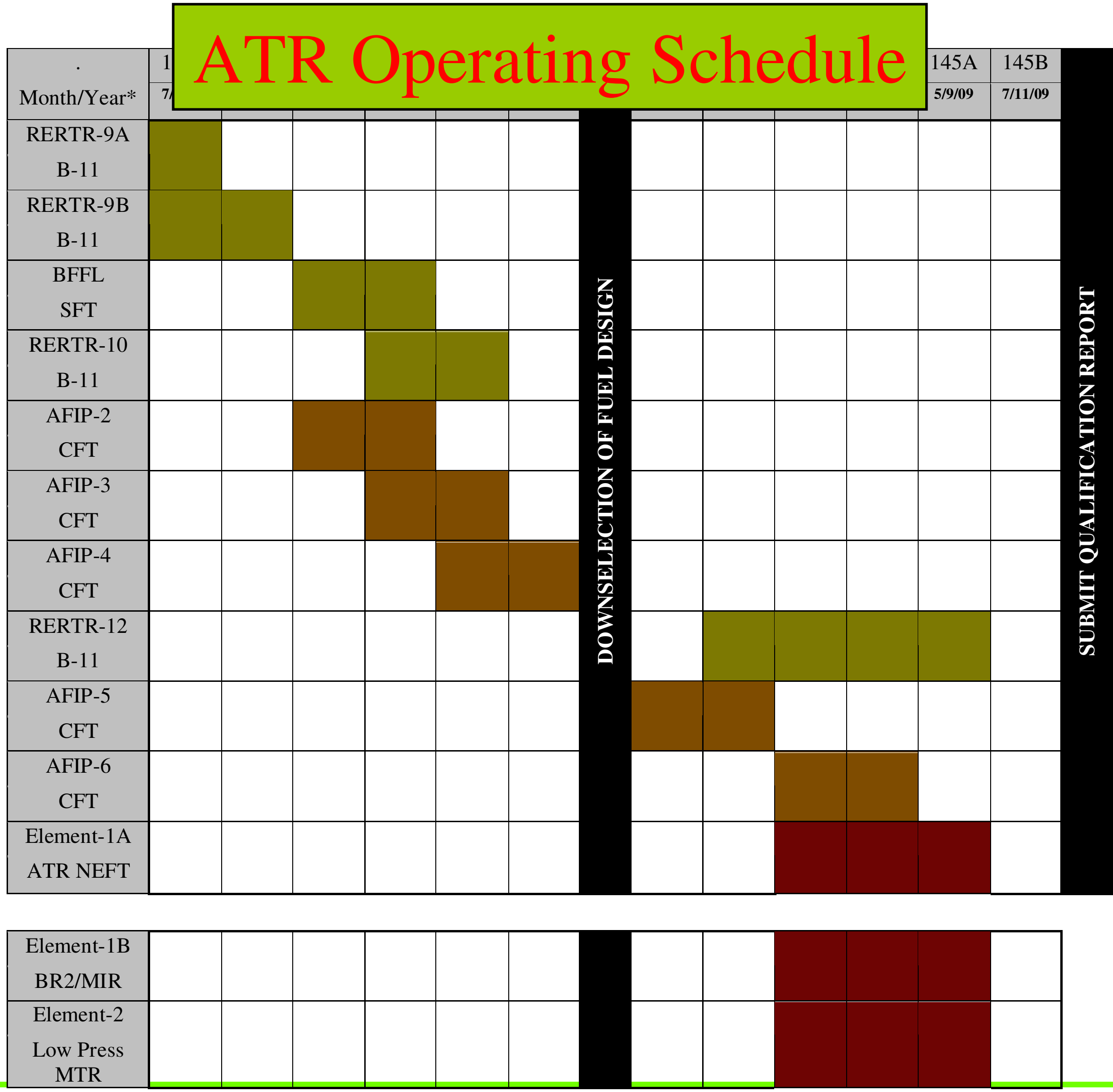
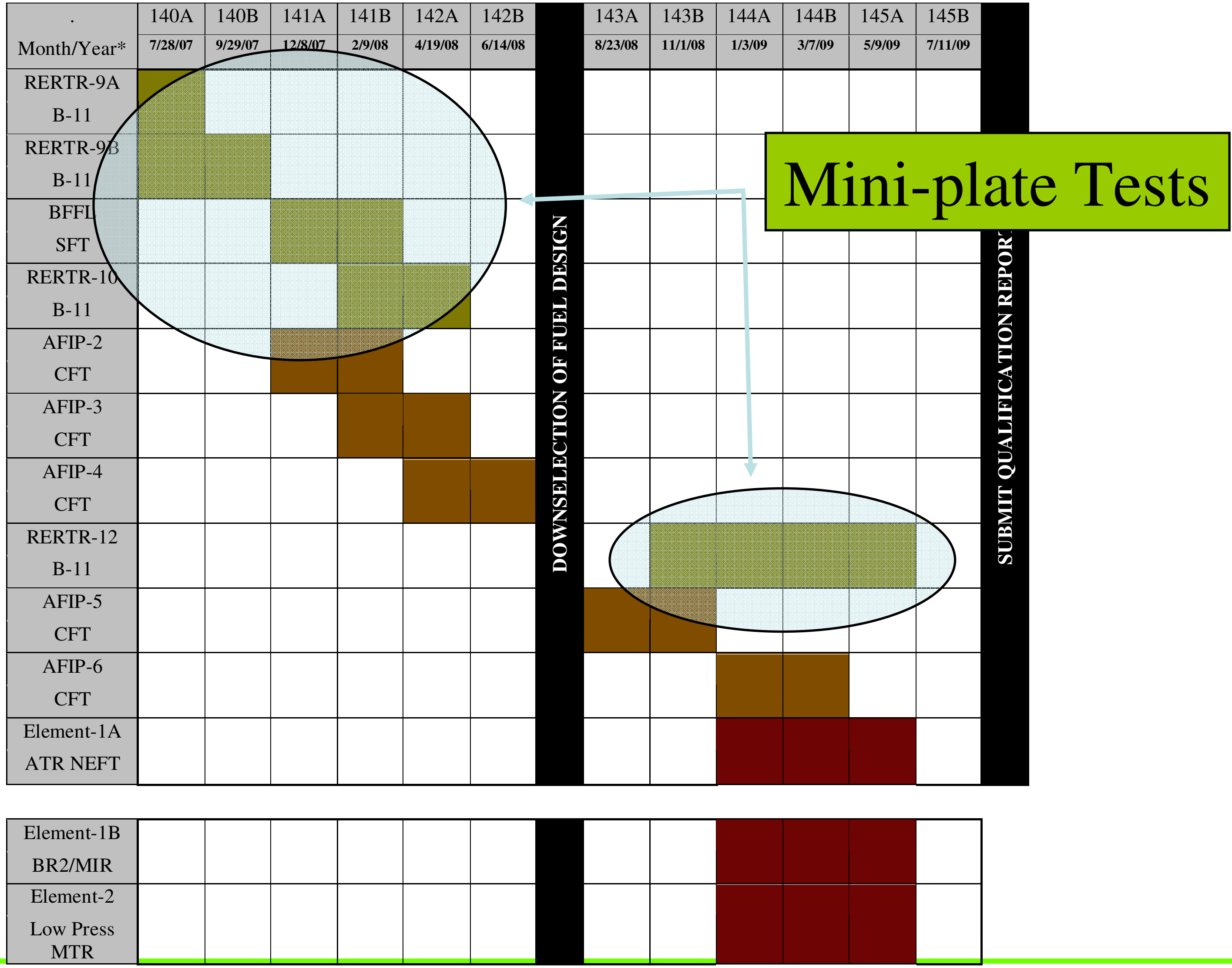
Monolithic Fuel Development Plan

. Month/Year*	140A 7/28/07	140B 9/29/07	141A 12/8/07	141B 2/9/08	142A 4/19/08	142B 6/14/08	DOWNSELECTION OF FUEL DESIGN	143A 8/23/08	143B 11/1/08	144A 1/3/09	144B 3/7/09	145A 5/9/09	145B 7/11/09	SUBMIT QUALIFICATION REPORT
RERTR-9A B-11														
RERTR-9B B-11														
BFFL SFT														
RERTR-10 B-11														
AFIP-2 CFT														
AFIP-3 CFT														
AFIP-4 CFT														
RERTR-12 B-11														
AFIP-5 CFT														
AFIP-6 CFT														
Element-1A ATR NEFT														
Element-1B BR2/MIR														
Element-2 Low Press MTR														

Monolithic Fuel Development Plan



Monolithic Fuel Development Plan

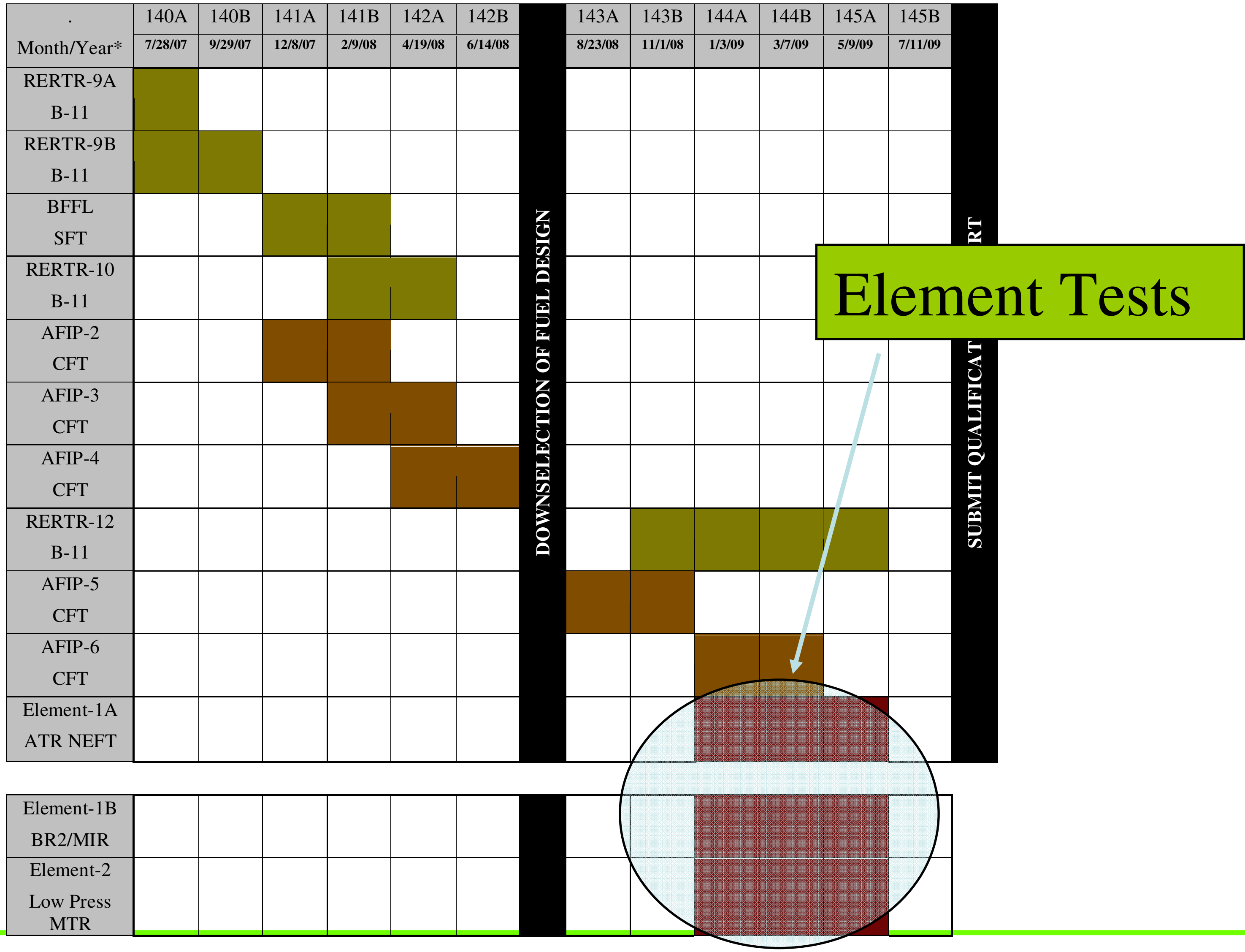


Monolithic Fuel Development Plan

Month/Year*	140A 7/28/07	140B 9/29/07	141A 12/8/07	141B 2/9/08	142A 4/19/08	142B 6/14/08	DOWNSELECTION OF FUEL DESIGN	143A 8/23/08	143B 11/1/08	144A 1/3/09	144B 3/7/09	145A 5/9/09	145B 7/11/09	SUBMIT QUALIFIC… EPORT
RERTR-9A B-11														
RERTR-9B B-11														
BFFL SFT														
RERTR-10 B-11														
AFIP-2 CFT														
AFIP-3 CFT														
AFIP-4 CFT														
RERTR-12 B-11														
AFIP-5 CFT														
AFIP-6 CFT														
Element-1A ATR NEFT														
Element-1B BR2/MIR														
Element-2 Low Press MTR														

Full-size Plate Tests

Monolithic Fuel Development Plan



Monolithic Fuel Development Plan

- **Fuel development activities will emphasis monolithic fuel form**
  - Demonstration of full size fuel fabrication
  - Fuel/clad interface behavior (chemical and mechanical)
  - Integrated mechanical behavior of fuel
- **Fuel performance demonstration**
  - Irradiation Tests
    - Mini-plates to evaluate chemical and irradiation properties
    - Full-size plates to evaluate integrated mechanical behavior
  - Fuel design downselection planned for end of FY08
  - Fuel qualification report to be submitted by end of FY09

Monolithic Fuel Development Plan

Fuel Design Downselection

. Month/Year*	140A 7/28/07	140B 9/29/07	141A 12/8/07	141B 2/9/08	142A 4/19/08	142B 6/14/08	DOWNSELECTION OF FUEL DESIGN	143A 8/23/08	143B 11/1/08	144A 1/3/09	144B 3/7/09	145A 5/9/09	145B 7/11/09	SUBMIT QUALIFICATION REPORT
RERTR-9A B-11														
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BFFL SFT														
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AFIP-2 CFT														
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RERTR-12 B-11														
AFIP-5 CFT														
AFIP-6 CFT														
Element-1A ATR NEFT														
Element-1B BR2/MIR														
Element-2 Low Press MTR														

Monolithic Fuel Development Plan

Qualification Report Submittal

. Month/Year*	140A 7/28/07	140B 9/29/07	141A 12/8/07	141B 2/9/08	142A 4/19/08	142B 6/14/08	DOWNSELECTION OF FUEL DESIGN	143A 8/23/08	143B 11/1/08	144A 1/3/09	144B 3/7/09	145A 5/9/09	145B 7/11/09	SUBMIT QUALIFICATION REPORT
RERTR-9A B-11														
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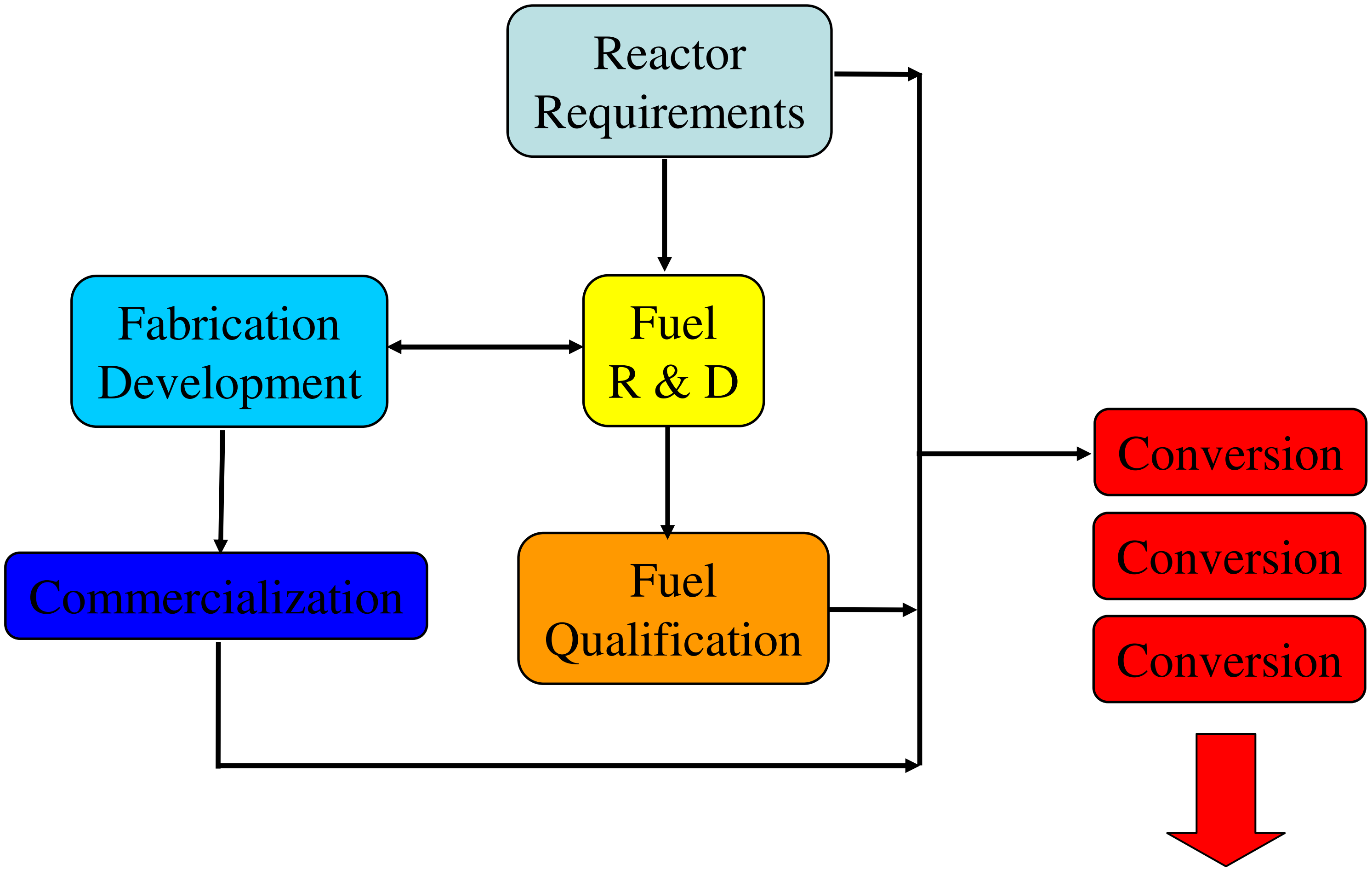
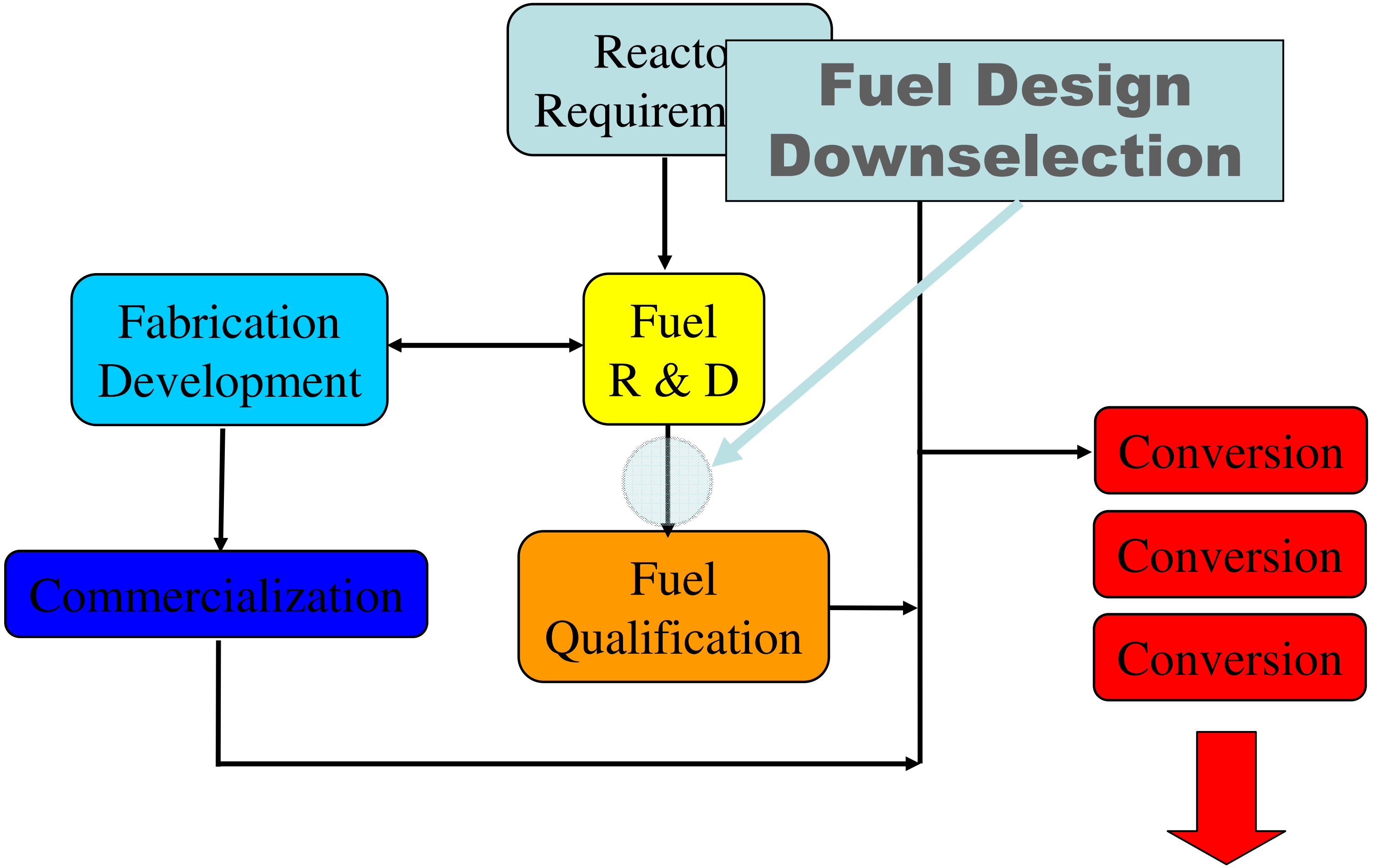
AFIP-5 CFT														
AFIP-6 CFT														
Element-1A ATR NEFT														

Element-1B BR2/MIR													
Element-2 Low Press MTR													

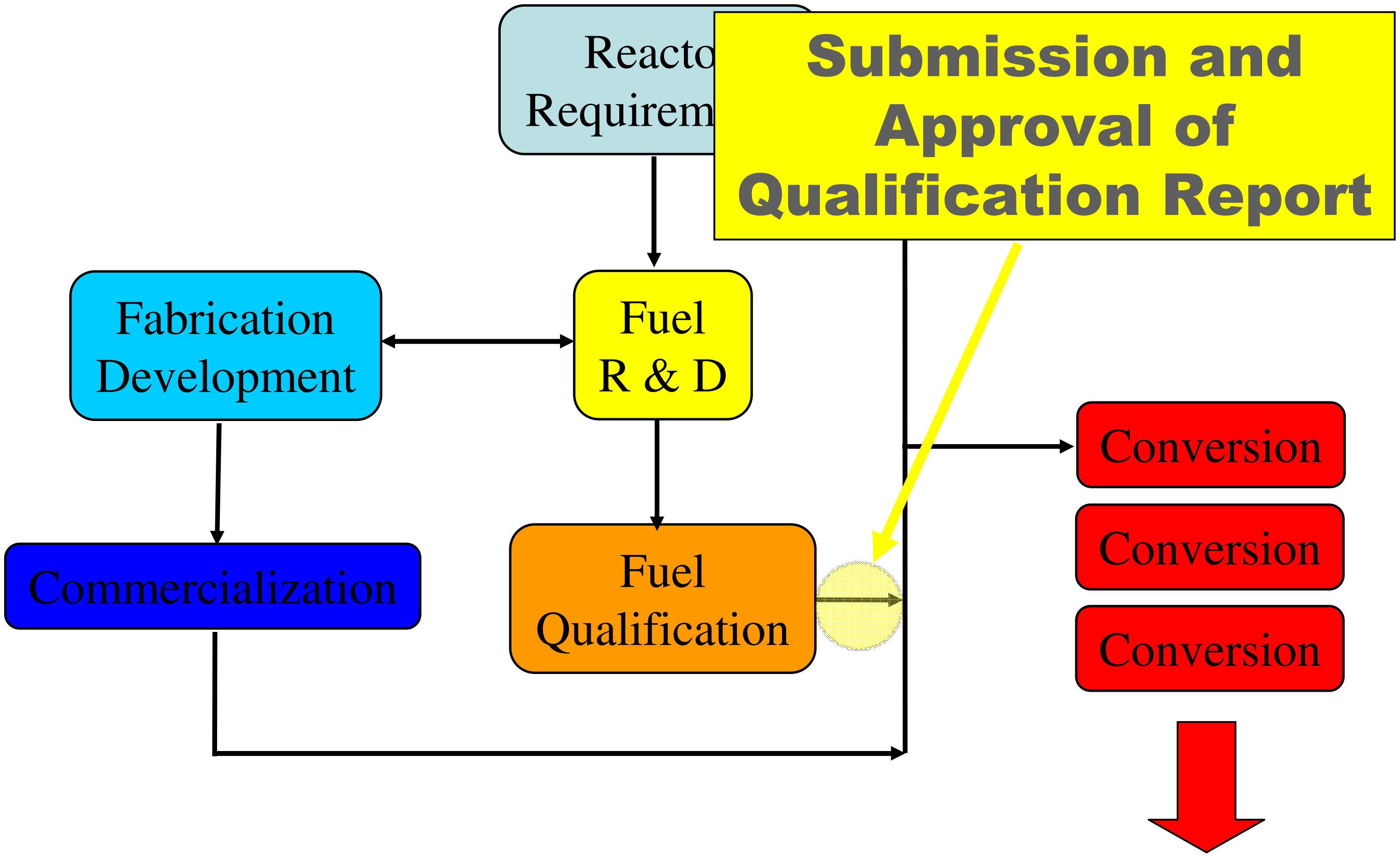
Fuel Development and Conversion



Fuel Development and Conversion



Fuel Development and Conversion



Conclusions

- U-Mo fuel has appeared questionable during the first stage of its development,
- We are now confident that U-Mo fuel will be capable to meet the HD fuel performance objectives
- The most promising remedies for dispersion fuel appears to be an addition of silicon to the matrix or the oxidation of the particles without any additive in Al matrix

Conclusions

- For monolithic fuel, tests are in progress to improve cohesion between foil and clad during and after irradiation
- Promising solutions include the application of a silicon rich layer to the interface between the cladding and fuel, application of a zirconium diffusion barrier to the interface, or by using Zy cladding co-rolled with the UMo foil
- 2011 as the first qualification target is probably ambitious, but considerable efforts are being applied at the international level to achieve this goal