MSRs Development in Russia

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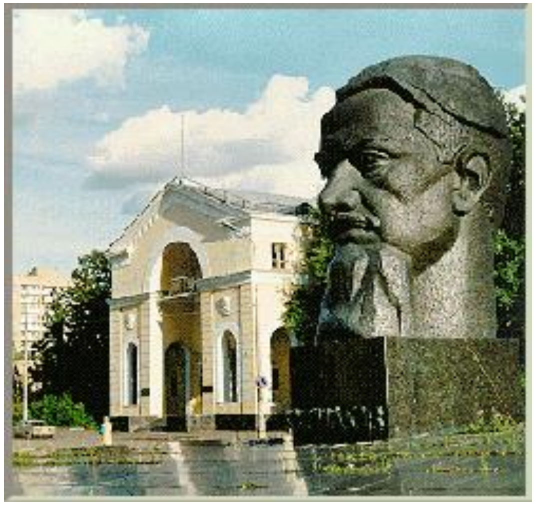


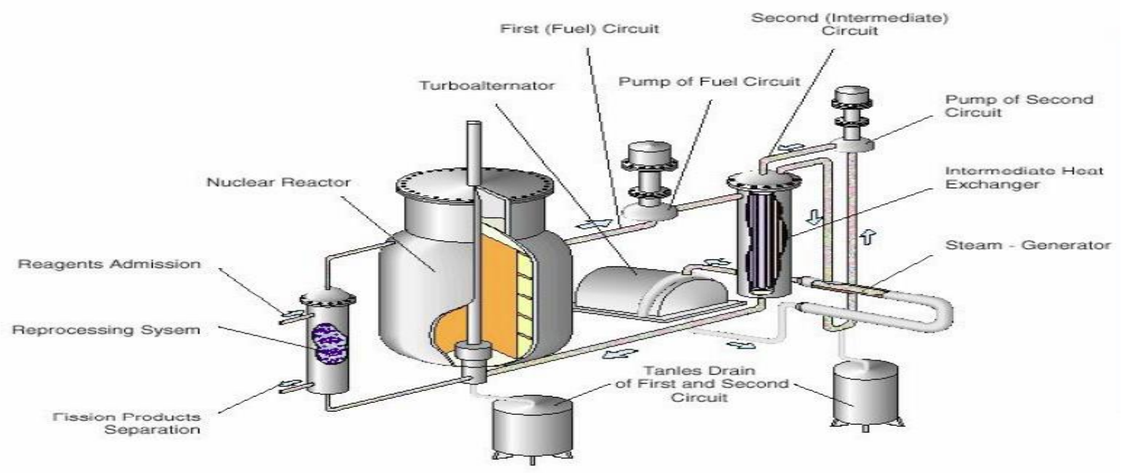
What are MSRs?

Usually in MSR fuel elements are replaced by liquids.

Physical Engineering Device (traditional solid fuel reactor) presumes that the fuel (solid) has to be used in a maximum condensed form that excludes reprocessing and has advantage of technical simplicity while reactor operating.

In Chemical Engineering Device (molten salt reactor) fuel circulates inside the core and out of the core as a coolant. Usually such kind of reactor has reprocessing system and combines on one site energy production and reprocessing plant.

MSR has all possibilities of general benefits such as unlimited burn-up, easy and relatively low cost of purifying and reconstituting of the fluid fuel, but also has some difficulties connected with specific potential gains.



Fuel	Liquid
	Solid
Fuel cycle	Th-U
	U-Pu
	Pu, MA
Solvent system	Fluorides
	Chlorides
Solid moderator	Yes
	No
Blanket	Yes
	No
Cooling	Outside core
	Inside core
Fuel processing	No
	Limited
	Full

MSRs Benefits and Difficulties

Benefits:

- Molten Salt Reactors in principle are more flexible than traditional ones.
- Energy production is not limited by possibility of heat removal inside reactor core so high meanings of neutron flux can be achieved.
- The possibility of continuous correction of liquid fuel salt content, together with radiation stability of the salts practically removes the limitations on fuel burn up .
- Fabrication, refabrication and transportation of fuel elements and spent fuel are excepted and back end part of fuel cycle is significantly simplified.
- Flexibility of the fuel cycle - the ability to work with fuels of various nuclide composition without reactor shutdown and special modifications of the core.
- High thermal efficiency, due to the high fuel salt temperature (>700 C);
- Operation in load follow mode.

Difficulties:

MSR technologies are much more complicated than those for solid reactors.

Experimental infrastructures (analytical and integral salt loops with real fuel salts) are required to obtain experience and proceed further mastering of MSR technologies and components testing (reprocessing system, pump, heat exchanger, etc.).

These works must go in paralell with creation of MSR conceptual designs within technological margins.

Othewise the conceptual design of MSR may stay « paper reactor ».

Molten Salt Reactors History

In the 60's and 70's in ORNL (USA) the favorable experience gained from the 8 MWt MSRE test reactor operated from 1965 to 1969 led to the design of a 1000 MWe molten salt breeder reactor (MSBR) with graphite moderated core , thermal spectrum and thorium-uranium fuel cycle. Even now this design is the example of the best justified MSR.

The technical feasibility of such systems now does not raise the doubts but for high breeding ratio MSBR demands continuous removal of soluble fission products and protactinium (removal time for lanthanides is about 30 days). Creation of such intensive system for fission products clean up in MSBR (first of all, for single stream one) is a challenge, in particular, remain difficulties on actinide losses to waste and selection of constructional materials for the fuel clean up unit. Beside these the calculations of last decade shown that MSBR concept exhibit very close to zero negative temperature reactivity coefficients and can't be regarded as the reactor type with inherent safety.

In Russia, the Molten Salt Reactor (MSR) program started in the second half of 1970th in Kurchatov Institute. The first years of work of the Molten Salt Reactor Laboratory was devoted to foundation of thermal/fast spectrum breeders of the MSBR type.

Last years main focus at Kurchatov Institute was placed on MSR cores without graphite moderator with fast spectrum of neutrons fueled by TRU's from LWR used fuel without uranium/thorium support. An innovative single stream concept, the MOlten Salt Actinide Recycler & Transmuter (MOSART) is developed by Kurchatov Institute since 2000. Last few years conceptual designs of two small MSRs for special needs (producing of medical isotopes and for North territories) were created.

MSRs for Contemporary Needs

In our days large scale long term development world nuclear energy system faces the problem of uranium resources and urgent needs to close the fuel cycle for all actinides as well to utilize thorium resources. In addition in many countries the scenario of Nuclear Power development is not very clear.

In such circumstances it will be required flexible power units for more effective electricity and high temperature production and closing of fuel cycle.

The ability to continually process FP's out of the MSR system changes the nature of accident scenarios and could allow for important innovations such as passive, inherent safety and a reduction of site emergency planning zones.

Low-pressure operation with chemically inert coolants allows for thinner walled components that are easier to fabricate and less expensive. Plant components could potentially be replaceable.

Nuclear energy systems employing liquid salt fuel present a promising option in response to the goals and criteria assigned to future nuclear systems: fuel cycle flexibility, safety, environmental impact, proliferation resistance, diversity of applications and economics. MSRs can be incorporated and often without changings of the design in any scenario of Nuclear Power development from breeding of new nuclear fuel to closing of Nuclear Power.

Within the GIF, research is performed on the MSR concepts, under the MOU signed by Australia, Euratom, France, Russian Federation, Switzerland and USA. China, Korea, Japan, and Canada are observers

Concept	Developer	Capacity MWt	Fuel / Coolant / Moderator
	Thermal		
Thorium Molten Salt Reactor, Liquid Fuel (TMSR-LF)	SINAP, China	395	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 /Graphite
Integral Molten Salt Reactor (IMSR)	Terrestrial Energy, Canada / USA	400	UF_4 / Fluorides / Graphite
ThorCon Reactor	ThorCon Int., Singapore	557x2	UF_4 / NaF-BeF_2 / Graphite
Liquid-Fluoride Thorium Reactor (LFTR)	Flibe Energy, USA	600	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 / Graphite
FUJI	MSR Forum, Japan	450	ThF_4-$^{233}UF_4$ / ^7LiF-BeF_2 / Graphite
Transatomic Power MSR (TAP)	Transatomic Power, USA	1250	UF_4 / LiF / SiC clad $ZrH_{1.6}$
Compact Used fuel BurnEr (CUBE)	Seaborg Technologies, Denmark	250	SNF /Fluorides / Graphite
Process Heat Reactor	Thorenco, USA	50	UF_4 / NaF-BeF_2, / Be rods
Stable Salt Thermal Reactor (SSR-U)	Moltex Energy, UK	300-2500	UF_4 /Fluorides / Graphite
	Fast		
Molten Salt Fast Reactor (MSFR)	France - EU - Switzerland	3000	ThF_4-UF_4 / ^7LiF
Molten Salt Actinide Recycler and Transformer (MOSART)	Kurchatov Institute, Russia	2400	$TRUF_3$ / ^7LiF-BeF_2 or NaF-^7LiF-BeF_2
U-Pu Fast Molten Salt Reactor (U-Pu FMSR)	VNIINM, Russia	3200	UF_4-PuF_3 / ^7LiF-NaF-KF
Indian Molten Salt Breeder Reactor (IMSBR)	BARC, India	1900	ThF_4-UF_4 / LiF
Stable Salt Fast Reactor (SSR-W)	Moltex Energy, UK	750-2500	PuF_3 / Fluorides
Molten Chloride Fast spectrum Reactor (MCFR)	Terra Power, USA	30	U- Pu / Chlorides
Molten Chloride Salt Fast Reactor (MCSFR)	Elysium Industries, USA	100-5000	U-Pu / Chlorides

6

MSRs in Russian Federation

From 1976 MSR study in Russia was organized around the following issues:

exploration of possible use and niches for MSR concepts

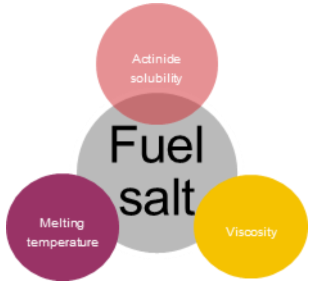
- *Efficient electricity production in Th-U Converter / Breeder designs*
- *Consumption of TRU's while extracting their energy*
- *High temperature Fluoride Salt Cooled Reactor*
- *Isotopes production for medicine*
- *Small MSR for far north territories*
- *Fusion hybrid blankets*

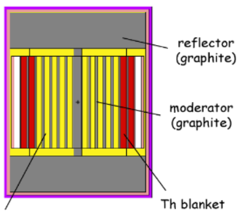
The work is divided into two main parts – theoretical and experimental

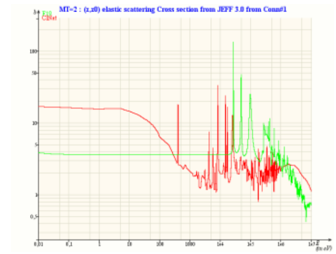
- *reactor physics, thermal hydraulics, fuel cycles and safety*
- *container materials for fuel and coolant salts*
- *physical and chemical properties of molten salt mixtures*
- *heat transfer and hydraulics of fuel and coolant salts*
- *handling and circulation of fuel and coolant salts*
- *process and radiochemical tests of model installations*
- *radiation chemistry of fuel salt*

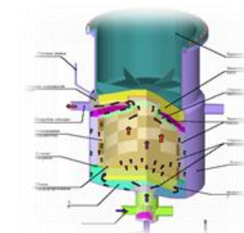
An extensive review of MSR development in Russia through 1989 is given in the book "Molten salt nuclear power systems - perspectives and problems" V. Novikov, V. Ignatiev, V. Fedulov, V. Cherednikov, Moscow, 1990

Material Challenges for the GEN IV MSR system
Selection of the Salt



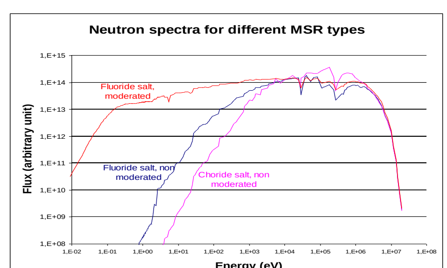






Liquid Fuel MSR

- Thermal
  - U → Fluoride → Terrestrial Energy IMSR, Thorcon
  - Th/U233 → Fluoride → SINAP TMSR, Flibe Energy LFTR
- Fast
  - U/Pu → Chloride → TerraPower, Elysium MCSFR
  - U/Pu → Fluoride → RF FMSR
  - TRU → Chloride
  - TRU/Th/U233 → Fluoride → RF MOSART
  - Th/U233 → Fluoride → EURATOM MSFR, RF MOSART



For thermal spectrum:

Positive feedback coeff.
Short graphite life span
Very low fuel initial inventory – no problems with solubility.
Test Reactor = MSRE

For fast spectrum:

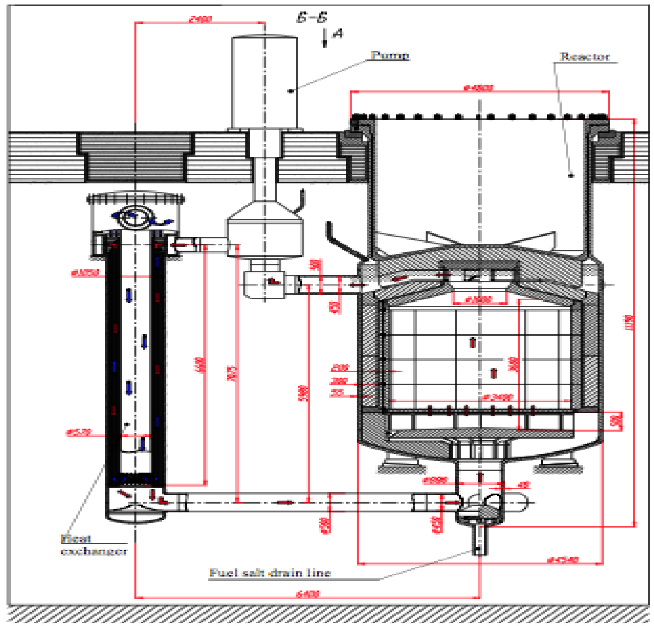
Very negative feedback coeff.
No problems with graphite life span
Large loadings
Chlorides or Fluorides – different horizonts of planning.

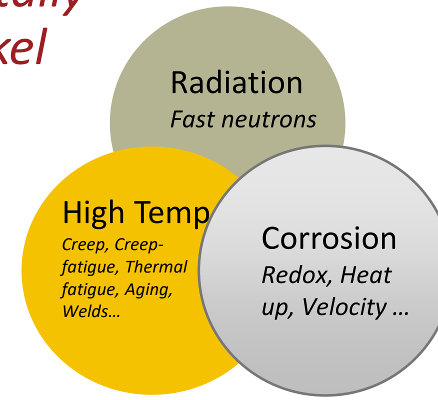
Selection of Materials for Components

Only two types of materials were proved experimentally for molten salts under irradiation – graphite and nickel alloys.

- Ni-based alloy
- Circuits, Heat exchangers *600 / 720° C* Creep, Creep-fatigue, Thermal fatigue, Aging, Welds…

- Ni-based alloy
- Intermediate circuit - *455 / 620° C* Aging, Welds, Compatibility $NaF\text{-}NaBF_4$, Oxidation, Wastage…





- Ni-based alloy / SS
- Vessel - *600° C* Negligible creep

- C, Ni
- Reflector *600-750° C* Negligible creep

- SiC
- Distribution plate- *600° C,*
- High irradiation

- *<u>Max temperature</u> of the fuel salt in the primary circuit made of special Ni- alloy is mainly limited by Te IGC depending on salt Redox potential*
- *<u>Min temperature</u> of fuel salt is determining not only its melting point, but also the solubility for AnF_3 in the solvent for this temperature*

Russian Molten Salt Test Loops

Loop	Melt, % mole	Volume, l	Alloy	$T_{макс}$, °C	ΔT, °C	Operation, hrs
SOLARIS	46,5LiF - 11,5NaF - 42KF	90	12kH18N10T	620	20	3500
KI C1	$92NaBF_4$- 8NaF	6	kHN80MT	630	100	1000
KI F1	72LiF- $16BeF_2$- $12ThF_4$+ UF_4	6	kHN80MTY	750	70	1000
KI M1	66LiF- $34BeF_2$ + UF_4	19	12kH18N10T	630	100	500
KURS-2	66LiF - $34BeF_2$ +UF_4	19	12kH18N10T	750	250	750
ISTC#1606	LiF- NaF- BeF_2+PuF_3	8	Ni - based	700	100	1600
ISTC#1606	LiF- NaF- BeF_2+ Cr_3Te_4	12	Ni -based	650	10	500
ISTC#3749	LiF- ThF_4- (BeF_2)+UF_4	8	Ni -based	750	100	1500
MARS	LiF-ThF_4- (BeF_2)+UF_4 + Cr_3Te_4	12	Ni -based	800	40	1500

- *A number of high-temperature MS test loops with forced and natural circulation was created and successfully tested.*
- *In laboratory and in reactor tests lasting from 500 till 3500 hrs at temperatures 500-800°C working capacity of loops components and system is shown.*
- *Modes of start-up and shut down installations are fulfilled and also ways for impurities removal and redox- potential measurement are improved.*
- *Questions of interaction with constructional materials, radiation resistance, heat and mass transfer in molten salt fluorides are studied.*

Alloys for MSR must be sustainable for RADIATION+HIGH TEMPERATURES+SALT CORROSION

Element	Hasteloy N US	Hasteloy NM US	HN80M-VI Russia	HN80MTY Russia	MONICR Czech Rep	E-721 France
Ni	base	base	base	base	base	base
Cr	7,52	7,3	7,61	6,81	6,85	8
Mo	16,28	13,6	12,2	13,2	15,8	0.7
Ti	0,26	0,5–2,0	0,001	0,93	0,026	0.3
Fe	3,97	< 0,1	0,28	0,15	2,27	0.63
Mn	0,52	0,14	0,22	0,013	0,037	0.26
Nb	-	-	1,48	0,01	< 0,01	-
Si	0,5	< 0,01	0,040	0,040	0,13	0.25
Al	0,26	-	0,038	1,12	0,02	0.05
W	0,06	-	0,21	0,072	0,16	10

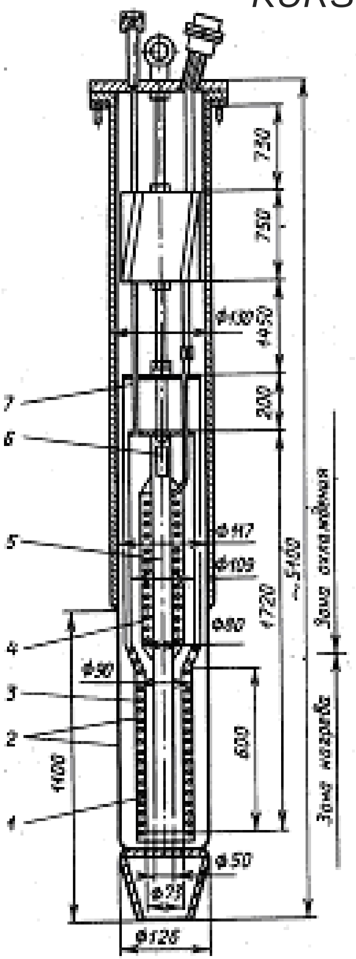
- *Experiments results in polythermal loops with redox potential control demonstrated that operations with Li,Be/F salt, also fuelled by UF_4 or PuF_3, are feasible using carefully purified molten salts and loop internals.*
- *Russian HN80MTY alloy with 1% added aluminum is the most resistant with fuel Na,Li,Be,Pu/F; Li,Be,U/F; Li,Th,U/F and Li,Be,Th,U/F salt mixtures up to temperature 750°C with [U(IV)]/[U(III)] ≤ 100. Corrosion rate was <5μm/yr. No intergranular corrosion of alloy is observed.*
- *Alloys modified by Ti, Al and V have shown the best post irradiation properties.*

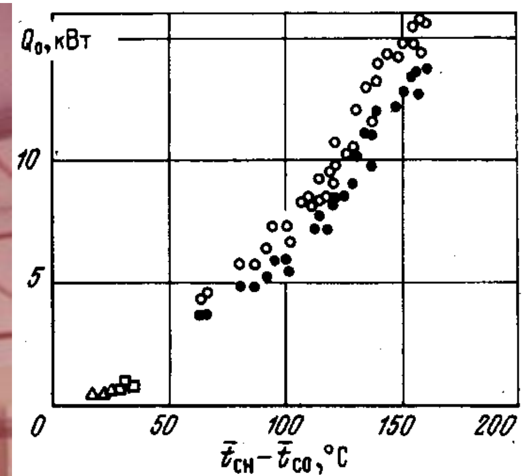
In temperature range 500-800^{0}C about 70 differently alloyed specimens of HN80MT were tested. Among alloying elements there were W, Nb, Re, V, Al and Cu

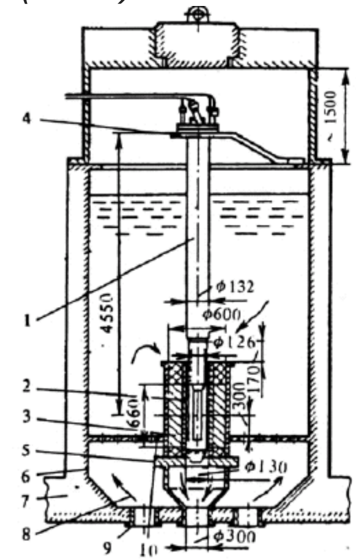
In Reactor Li,Be,U/F Natural Convection Loop

KURS-2 exposure time~ 750 hrs

$T_{мах}$=750 °C; Φ = 0,76•10^{14} neutron/(см^2•s)

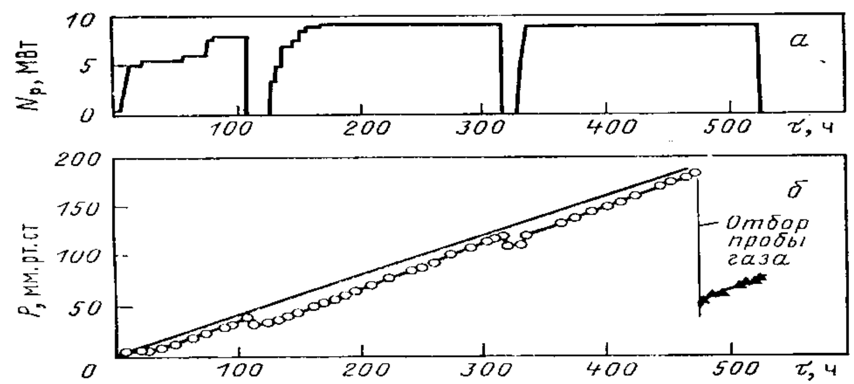






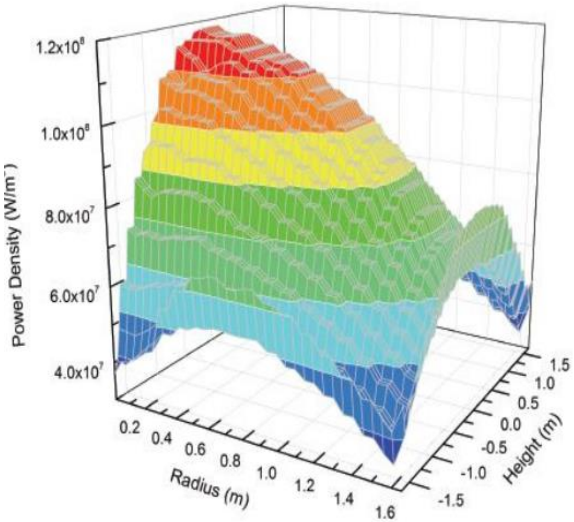
Helium was generating through reaction

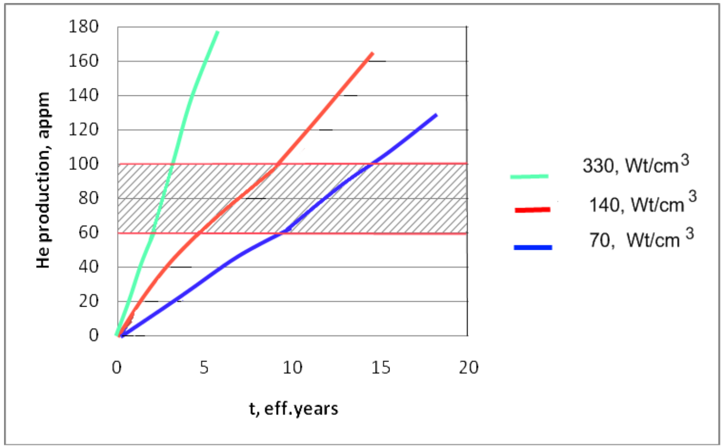
6LiF + ^{1}n → He + 1/2T_2 + 1/2F_2

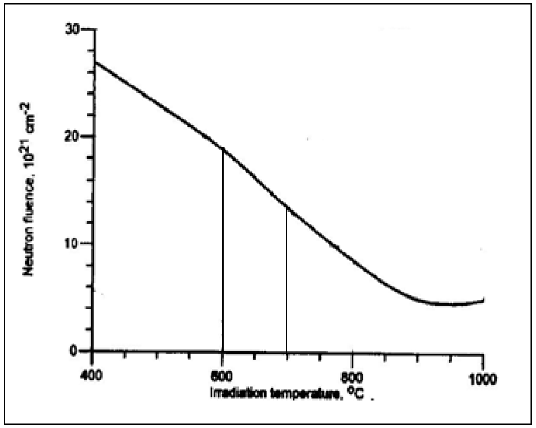


Measured F evaluation by radiolysis corresponded to 3·10 $^{-6}$ молmolecule per 100 eV absorbed

IN MOSART CORE THE LIMITATIONS ON THE RADIATION RESISTANCE OF STRUCTURAL MATERIALS, ALONG WITH THE POSSIBILITIES OF HEAT REMOVAL, REPRESENT THE MAIN FACTORS THAT INHIBIT THE INCREASE IN THE CORE SPECIFIC POWER > 140 W / CM^3







The temperature in the fuel circuit due to the decay heat without heat sink should not reach the maximum temperature for the structural material

He embrittlement for Ni-base alloy at T > 500°C

$^{58}Ni + n \rightarrow {}^{55}Fe + {}^{4}He$, (>1MeV);

$^{60}Ni + n \rightarrow {}^{57}Fe + {}^{4}He$;

$^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$.

$^{58}Ni + n \rightarrow {}^{59}Ni + \gamma$, $^{59}Ni + n \rightarrow {}^{56}Fe + {}^{4}He$.

Basing on neutron fluence (3,8*10^{21}n/(cm^{2}yr)) and temperature (860-1000K) reflector should be changed in 5 yrs

13

Summary

- ***The molten salts reactors are very flexible systems which can be incorporated in any scenario of Nuclear Power Development.***

- ***A successful burner or breeder systems could be developed on the base of MSR systems after large number of formidable problems which must be experimentally solved. Several of these have been solved, and some seem to be well on the way to solution but this work must go in parallel with MSR systems designing.***

- ***Main focus at Kurchatov Institute (RF) is placed on MSR cores without graphite moderator with fast spectrum of neutrons fueled by TRU's from LWR used fuel without uranium/thorium support. An innovative single stream concept, the MOlten Salt Actinide Recycler & Transmuter (MOSART) is developed by.***
- ***Last few years conceptual designs of two small MSRs for special needs (producing of medical isotopes and for North territories) were created.***