Heavy metal coolant for nuclear power applications

A very personal story of technology transfer from Soviet military secret data base to open research in Europe and worldwide.

My own contribution to HISTORY

Waclaw Gudowski
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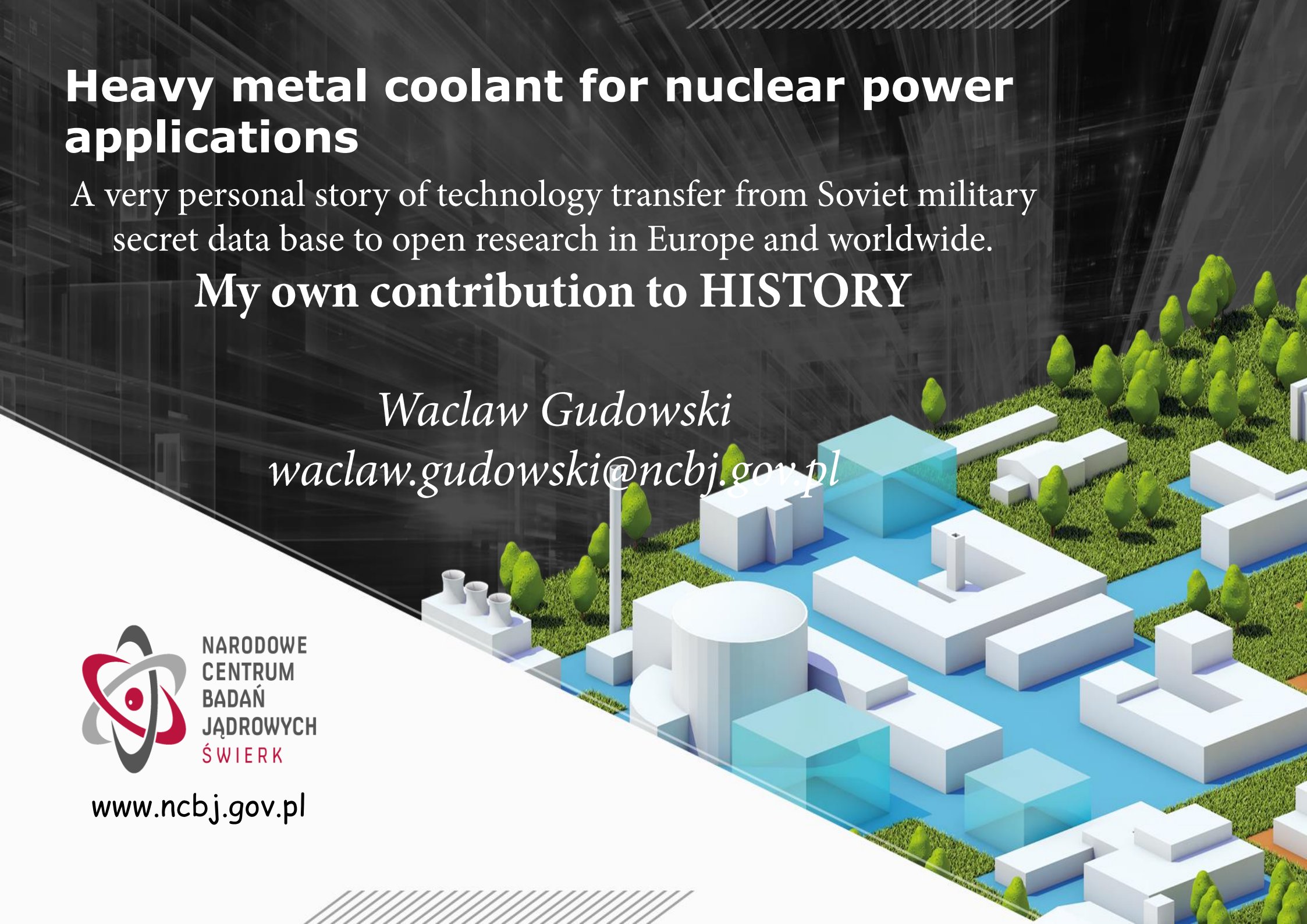

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Outline

Few words about photos

Father of ADS and heavy metal coolant concepts

Metal coolants investigated for reactor coolants

First metal cooled reactors

Pb-Bi coolant for Soviet nuclear submarines

Heavy metal cooled reactor concepts under current development in Russia

How this technology was pulled out from the Russian military high secrecy “data bank”

Period 1991-1995

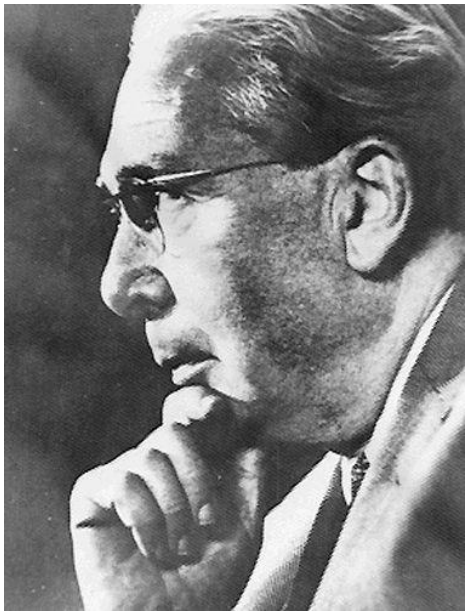
Workshop in Trento 1997

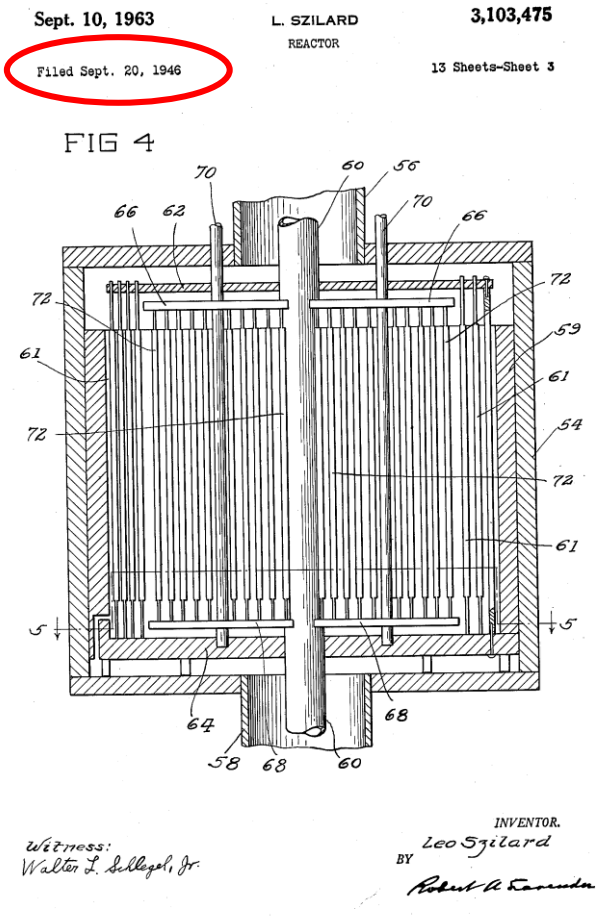
Stormy development of HM coolant research after workshop in Trento

Who should be considered as a father of HM coolant technology for nuclear power application?

Who should be consider as a father of HM coolant technology for nuclear power application?

Leo Szilard of many reasons





Sept. 10, 1963 L. SZILARD 3,103,475

REACTOR

Filed Sept. 20, 1946 13 Sheets-Sheet 3

FIG 4

Witness: Walter L. Schlegel, Jr.

INVENTOR. Leo Szilard

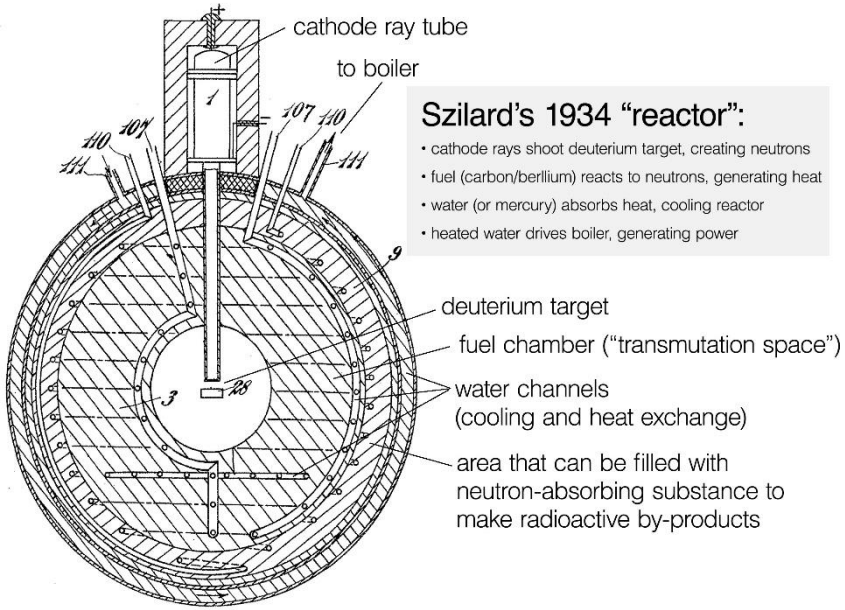
BY Robert A. Lavender

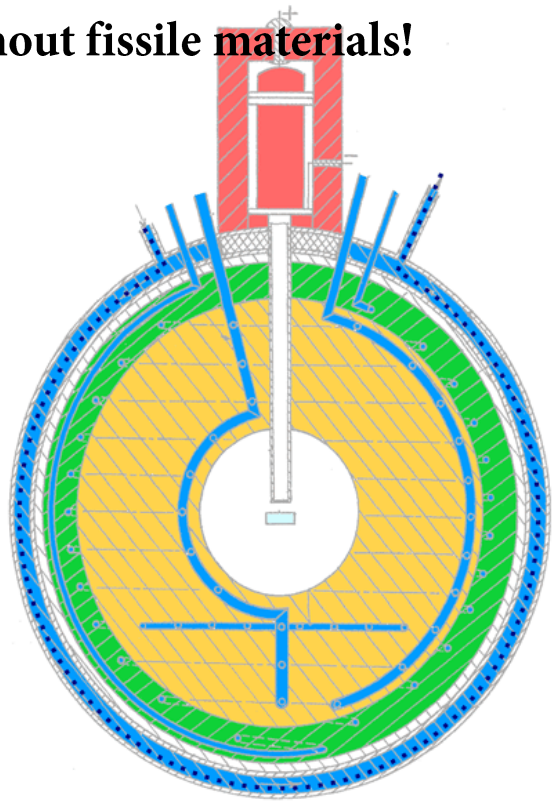
In this embodiment the chain reaction may be controlled by various methods such as by introducing into the chain reacting mass or reactor 2 at the center or core there of a quantity of liquid, such as **molten lead or a lead- bismuth alloy** capable of slowing the neutrons to a limited extent.

Who should be considered as a father of HM coolant technology for nuclear power application?

Leo Szilard of many reasons.

Father of an ADS concept! A reactor without fissile materials!





Liquid metals suitable as nuclear reactor coolant

Liquid metal	Occurance, % of weight	T_{melt} (C)	Cost $/kg	Chemical activity	Corrosivity	Toxicity
Lithium, Li	0.002	180.5	115	Less than Na and K	More corrosive than Na and K	More toxic than Na, K
Sodium, Na	~2.4	97.8	3	High	Low	Low
Potassium, K	~2.1	63.5	13	High	Low	Low
Mercury, Hg	$\sim 8.5 \cdot 10^{-6}$	-38.8	38	Low	High	High
Lead, Pb	0.016	327.5	2	Low	High	High
Bismuth, Bi	$\sim 10^{-5}$	271.4	10	Low	High	High
Na-K		-11		High	Low	Low
Pb-Bi		123.5		Low	High	High
Cs	$6.5 \cdot 10^{-4}$	28.4	73000	Medium	Low	Low
Gallium, Ga	0.0019	29.8	360	Fairly, medium	High	High

Price of graphite

Depends on many factors like purity, density etc.

For HTGRs can be expected to be around 1000-2000 €/ton
i.e. about 1-2 €/kg

Liquid metal coolant choices

- Sodium - for fast breeder reactors
- Pb-Bi eutectic - for nuclear submarines (Soviet Union)
- Na-K, sodium-potassium eutectic – for space propulsion reactors, with a vision to use Li in the future

FIRST "NUCLEAR" ELECTRICITY PRODUCED BY EXPERIMENTAL BREEDER REACTOR – I (SODIUM-POTASSIUM EUTECTIC COOLED)

IDAHO, DECEMBER 20, 1951

In the beginning of the 1950's nearly at the same time the USA and USSR launched the development of the nuclear power installations for nuclear submarines. In both countries the work was carried out for two types of reactors: with pressurized water reactors and reactors cooled by liquid metal coolant (LMC).

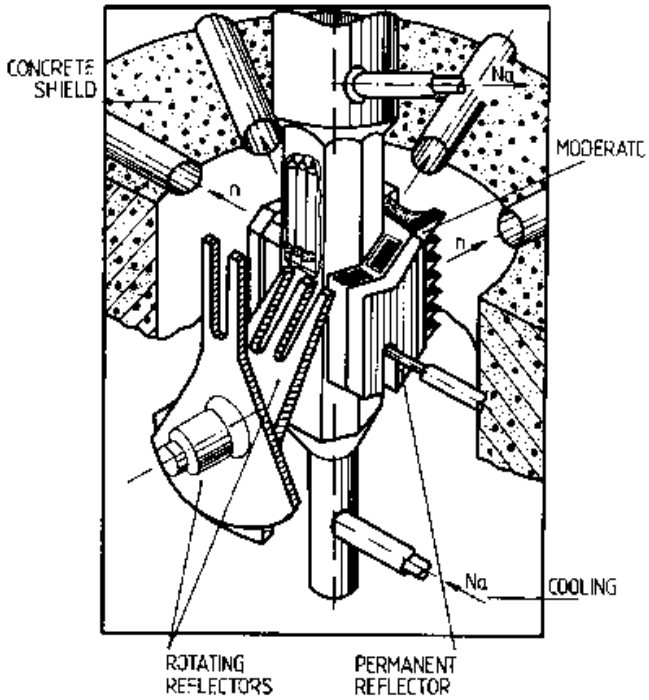
In spite of Szilard's work – or maybe because of that - in the USA sodium (sodium-potassium) was chosen as LMC as it possessed better thermo-hydraulic characteristics. Fermi-1 reactor has been built and the experimental nuclear submarine **"Sea Wolf"** were constructed.

Seawolf (SSN-575) - commissioned 30 March 1957 (5 years of construction). Reactor S2G (**S**ubmarine, **2**nd generation, **G**eneral Electric) – sodium cooled, but not "that fast" (had graphite inside its core) – 78 MWt. Replaced by PWR – S2W after only about 1 year of operation

"Blue Haze"
Sometimes, for example, the Seawolf's hull would glow in the dark.

Physical start-up of the sodium cooled research reactor IBR-2 in Dubna, 1977.

Physical start-up of the sodium cooled research reactor IBR-2 in Dubna, 1977. Moving reflector design – my work



In the USSR in early 50's the lead-bismuth eutectic alloy was chosen as major LMC and parallel development to PWRs in submarines.

The problems of coolant technology, structural materials corrosion and compatibility as well as mass transfer have been solved as a result of coordinated work of several organizations: IPPE-Obninsk, Material Research Center "Prometey", "Gidropress" - Podolsk, OKBM, NIKIET + more for about 15 years..

1955-1958 the first Pb-Bi reactor for submarine propulsion has been commissioned at IPPE Obninsk – so called 27/VT1 reactor. About 70 MW

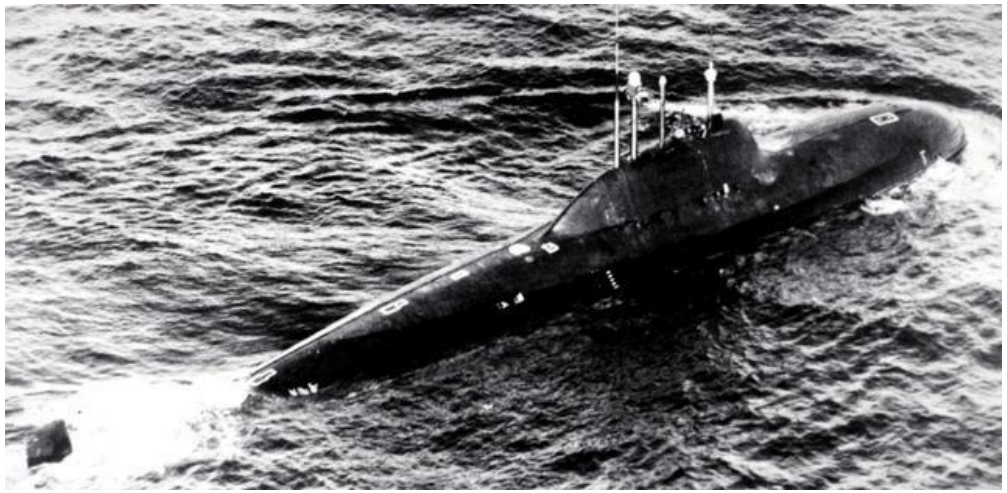
Full scale : ” Project 645 November-ZhMT”. Commissioned on 30 October 1963, **as K-27 submarine**.

On 24 May 1968 about one-fifth of the reactor core had experienced inadequate cooling caused by uneven coolant flows. Hot spots in the reactor had ruptured, **releasing nuclear fuel and nuclear fission products into the liquid-metal coolant**, which circulated them throughout its reactor compartment. 9 people died within few days.

Next, improved submarines propelled by Pb-Bi cooled reactor

7 ALPHA class submarines ”Lyre” built 1977–1981 (served until 1996). **Powered by one 155 MWt reactor** (type OK-550 or BM-40A).

The fastest submarines built, over 41 knots submerged. The fastest was, however, K-222, 2 PWR reactors – 177 MWt, 44.7 knots



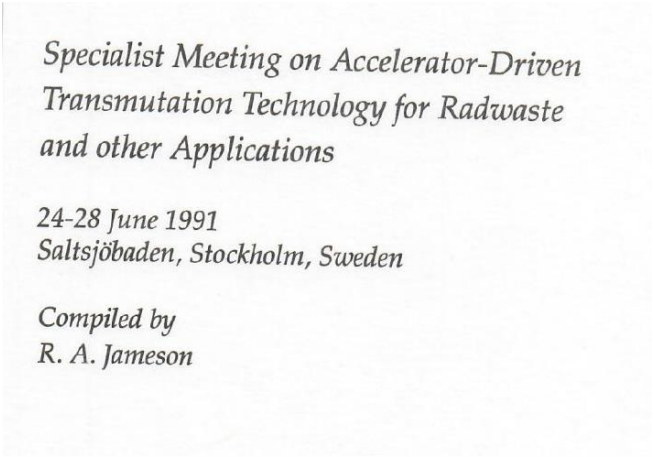
Civilian concepts of Pb-Bi and Pb-cooled fast reactors have been developed in parallel within the Soviet/Russian defense complex. They evolved **now** to:

SVBR-100 reactor (Gidropress-IPPE Obninsk-private)
and
the project ”Proryv” - BREAKTHROUGH –
BREST-300/1200 Pb-cooled reactor (Rosatom)

How this technology was pulled out from the Russian military secrecy

1991 – Fall of the Soviet Union. Comprehenesive Threat Reduction Treat comes with help. Senators Nunn-Lugar associated alltid with this program. Russia very cooperative in receiving support for non-proliferation and cleaning nuclear MESS!

1991 - Meeting in Saltsjöbadet. First meeting of ”STAR WAR SCIENTISTS” of USA and Russia. Very instrumental for this meeting was our late colleauge Curt Mileikowsky. **ADS and nuclear power in general recognized as a possible peaceful international cooperation between Russia and West World. HM coolant identified as an important technology for cooperation with Russia.**



Specialist Meeting on Accelerator-Driven Transmutation Technology for Radwaste and other Applications

24-28 June 1991
Saltsjöbaden, Stockholm, Sweden

Compiled by
R. A. Jameson

How this technology was pulled out from the Russian military secrecy

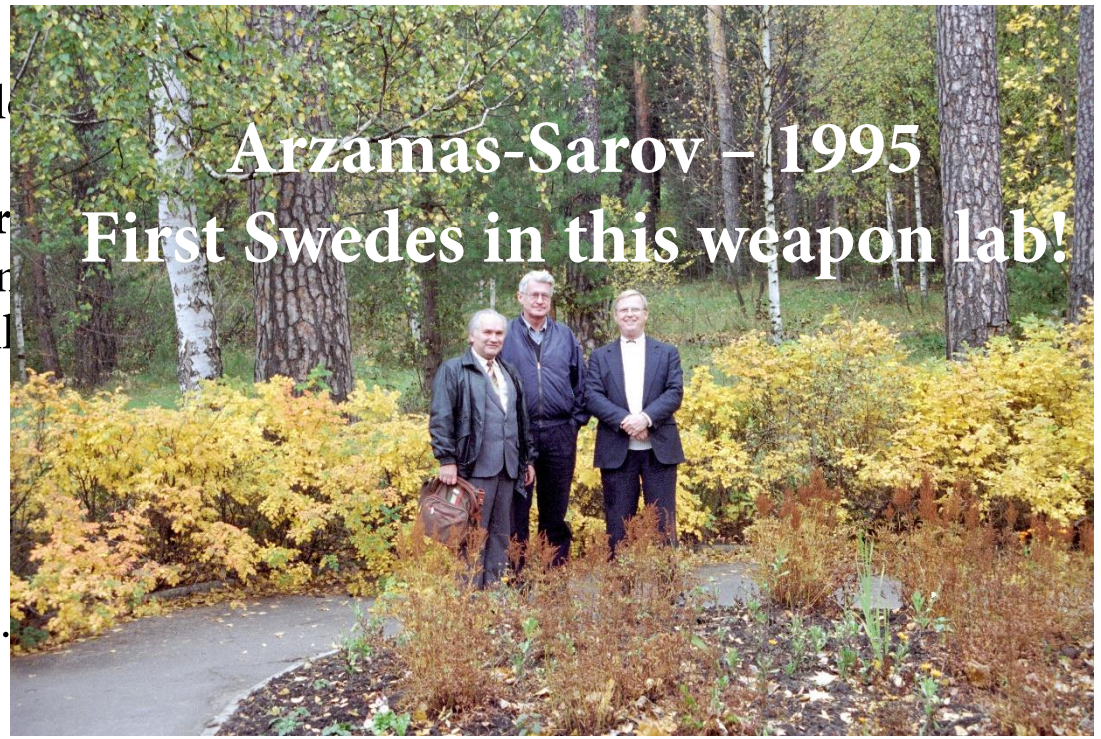
1992 – ISTC – International Science and Technology Center agreement signed by pres. Yeltsyn

1993 - Preparation of the program of the ISTC **Project 17 (Weapon Grade Pu disposal options)**: Studies of different spallation target concepts included. Collaboration ITEP-IPPE. Project #17 and its program stimulated by Los Alamos National Lab. (E. Heighway, A. Sullivan and ADTT-Office) and KTH!!

1994 – ISTC starts to operate and P17 approved.

1994 – The First ADTT Conference in Las Vegas. Massive Russian participation. First ideas about a dedicated project for Pb-Bi technology

How this technology was pulled out from the Russian military secrecy. Conference in Las Vegas and a visit to nuclear weapon lab – Arzamas-Sarov



How this technology was pulled out from the Russian military secrecy

1994 –

KTH International Symposium : ”Nuclear Technology Today and in the Future (H. Blix – IAEA, C. Bowman – LANL). HM coolant technology in focus

Swedish Network for Transmutation Research – KTH, UU, CTH, MSI (W. Gudowski, H. Conde, C. Mileikowsky)

Swedish and then INTERNATIONAL Contact Expert Group on ISTC Transmutation related Projects – funding transmutation projects in Russia, collaboration with LANL and CEA. Waclaw Gudowski chairing this group until 2006

Intensive Studies of first concepts of liquid metal and quasi-liquid spallation targets. From lead-ball suspensions in the heavy water to windowless liquid Pb/Bi target

Swedish and then INTERNATIONAL Contact Expert Group on ISTC Transmutation related projects

How this technology was pulled out from the Russian military secrecy

1995 –

KTH (Gudowski) chairs IAEA Status Report on ADS research. ADS acronym coined, a lot of emphasis on HM coolant technology

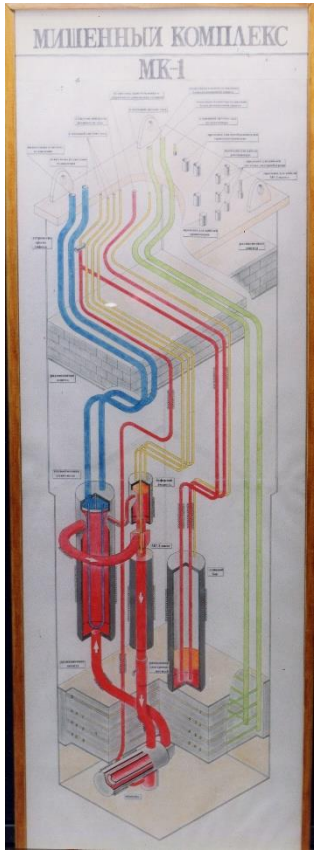
Gunter Bauer

In close collaboration with Los Alamos National Laboratory (ADTT office) Swedish Spallator Group proposed the liquid **Pb/Bi target manufacturing at IPPE** in the frame of ISTC-financing. **The idea was to manufacture the target in Obninsk and then irradiate the target and conduct all the necessary experiments on LANL-accelerator. Swedish financing for this idea supportted by the Swedish Ministry of Foreign Affairs managing Swedish contribution to ISTC.**
Mid 1995 - invitation of IPPE vice-director B. Gromov and E. Efimov **to Stockholm for discussion on "target"project.** Invited also G. Bauer from PSI - Zürich (responsible for spallation target at PSI and spokesman for ESS - European Spallation Source). 50 k$ project financed by PSI for pre-conceptual spallation target design to evaluate the costs of target manufacturing.

How this technology was pulled out from the Russian military secrecy

1995 –

US (and not only) idea was to make “reverse engineering” of the delivered Pb-Bi spallation target. W. Gudowski strongly opposed that option and tried other options.



How this technology was pulled out from the Russian military secrecy

1996 –

2nd ADTT Conference in Kalmar (Sweden), collaboration KTH/UU/CTH/MSI. Over 200 participants from 24 countries. Very strong representation of Russia on special invitation of W. Gudowski and ensured ISTC support

2 first European projects in ADS. Strong emphasis on Pb-Bi technology:
Impact of Accelerator Based Transmutation on Nuclear Fission Safety - **IABAT**. Coordination – KTH (W. Gudowski). Russian groups from IPPE and Sosny Institute in Belorus exclusively invited to this European project. A very unusual at project at that time.
Transmutation through Adiabatic Resonance Crossing (TARC)- Coordination – CERN (C. Rubbia). “Lead neutron spectroscopy”

2nd ADTT Conference in Kalmar (Sweden), collaboration KTH/UU/CTH/MSI. Over 200 participants from 24 countries.

How this technology was pulled out from the Russian military secrecy

1996 –

199 June - US-veto on ISTC board meeting for the Pb-Bi spallation target. Project postponed - no clear willingness for financing from other ISTC partners than Sweden.

W. Gudowski makes "shuttle diplomacy" between US-EC-Russia

1996 - Summer-Fall - Organizing European support for Project 559. CEA-Cadarache got "on-board" with a strong support. **Slow process of understanding that this project may have a crucial importance for the future of accelerator driven transmutation systems and technology transfer in HM coolant technology.** Los Alamos after lobbying from Sweden successfully alters the position of DOS.
1996, November – Target project approved on the ISTC Board Meeting as Project #559. Financing: US-500 K$, EC - 250 k$, Sweden - 250 k$.

W. Gudowski makes “shuttle diplomacy” between US-EC-Russia

Obninsk 1996


Cadarache - 1996


Brussels - 1996

How this technology was pulled out from the Russian military secrecy

1997 –

January and March - work on the final working plan for #559 (LANL + Sweden actively participating: S. Wender, **F. Venneri** - LANL, W. Gudowski, C. Mileikowsky and H. Condé - Sweden)

"James Bond mission" – Waclaw Gudowski and Curt Mileikowsky collect privately 60 k$ for covering an international IPPE patent on Pb-Bi technology. Changes at IPPE directorship, new directors, new policy, some friction popped up.

W. Gudowski "smuggles in" money (60 k$) to Russia, to IPPE to offer funding for international patent processing. After 2 days of discussion and tough arguments IPPE contacting the government declines a pantent option and OFFERS INSTEAD PUBLISHING OF ALL IMPORTANT ASPECTS of Pb-Bi technology. Agreement on dedicated international seminar on HM in nuclear technology. Waclaw Gudowski **SMUGGLES BACK** 60 k$.

How this technology was pulled out from the Russian military secrecy

1997 –

European Technical Working Group on ADS Research formed. Pattern of the Swedish CEG under Carlo Rubbia Chairmanship

Trento Worskhop

- IPPE and other Russian partners got permission to disclose publicly the key Pb/Pb-Bi coolant technology issues and to discuss further projects related to transfer of this technology to public domain

How this technology was pulled out from the Russian military secrecy

1997 –

TRENTO WORKSHOP!
Start of many European and world-wide research projects

A special HM coolant technology seminar at MIT. Huge interest and standing ovation for IPPE presentation

See:
https://youtu.be/J1OPqNgAuSk

To. Gudowskii

Alexander Ilyich Leipunskii (1903-1972)

One of the founders of the IPPE. A member of Ukraine Academy of Sciences, he worked in the IPPE in 1949-1972, was a scientific supervisor of the institute and of all the trends of liquid metal reactor design.

In the early 1950s academician Leipunskii suggested using lead-bismuth eutectic as a coolant in nuclear reactors of transport systems.

Lead-Bismuth eutectic was chosen for its unique qualities.

IPPE, Obninsk, Russia

Methods to regulate the dissolved oxygen concentration in the coolant

When the increasing or the reducing of dissolved oxygen concentration at the appropriate temperature regimes, the reinforcement of mass transfer processes takes place, causing the slagging of the cold zones or dissociation of the protective film of the structural material in hot zones.

Regulation system of dissolved oxygen in the coolant and purification system should provide for the optimum oxygen regime.

It is recommended to use three processes:

1. **Delivering into the loop of gaseous oxygen (auxiliary method).**

$$O_2 + 2Pb = 2PbO$$

$$PbO \rightarrow Pb + |O|$$

2. **Delivering into the loop of water vapor and hydrogen mixtures (main method).**

$$|O| + H_2 \Leftrightarrow H_2O$$

3. **Regulation by using solid oxidant.**

$$PbO \rightarrow PbO + |O|$$

IPPE, Obninsk, Russia

How this technology was pulled out from the Russian military secrecy

1997 –

Swedish Academy of Engineering Sciences hosts International Seminar on Transmutation (C. Rubbia - CERN, S. Schriber – LANL, M. Salvatores – CEA, F. Venneri – LANL, W. Gudowski - KTH). Stimulating many European activities

IAEA Status Report on ADS research published raising a big interest

How this technology was pulled out from the Russian military secrecy

1997 –

W. Gudowski “converts” the Swedish Expert Group into the International Contact Expert Group on ISTC Transmutaion related Projects. Chairs this Group. Coordination of about 20 projects in Russia of about 10 M€.

1998 -

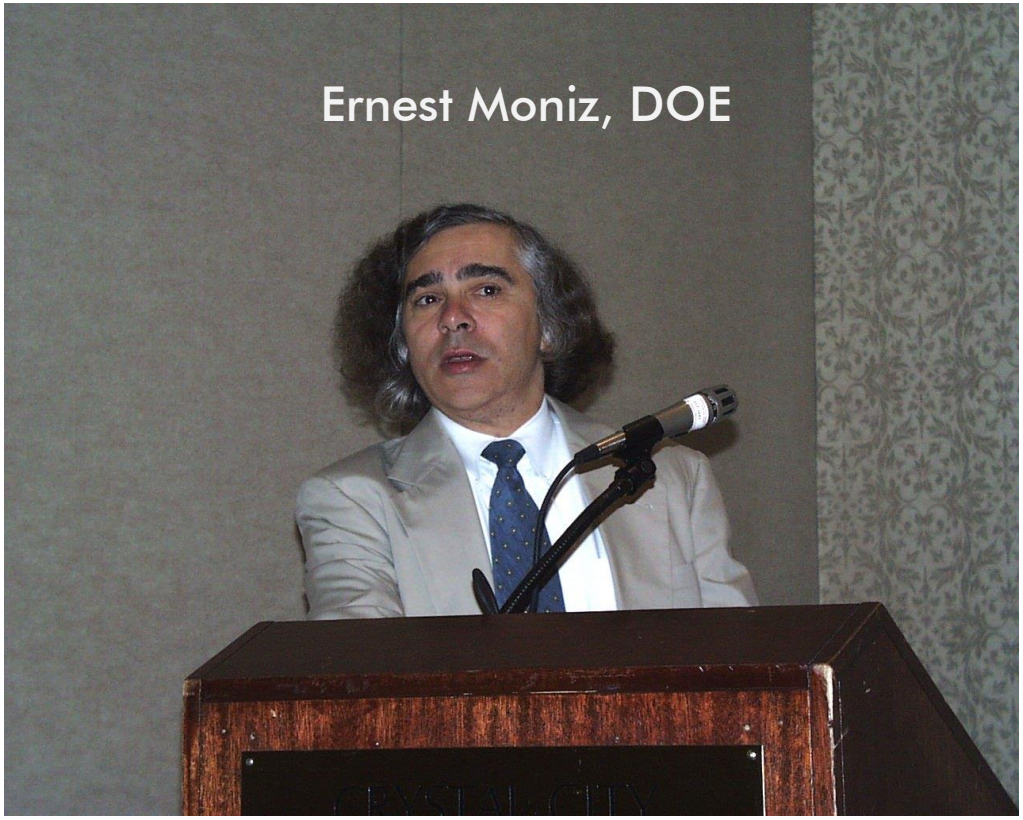
W. Gudowski actively promoting HM technology as a member in "Nuclear Physics Group" of "OECD- MegaScience Forum"

1999 -

W. Gudowski invited to the International Expert Group for US Department of Energy ATW/ADS-Roadmapping activity and GenIV initiative group
Member of the European Technical Working Group on ADS Research
KTH actively prepares European projects for 5th FP
Programme Committee of the 3rd ADTT Conference in Prague
Coordinates and supervises subcritical experiment in Minsk (YALINA)

"Nuclear Physics Group" of "OECD- MegaScience Forum" – Paris 1998

International Expert Group for US Department of Energy ATW/ADS-Roadmapping activity and GenIV initiative group



How this technology was pulled out from the Russian military secrecy

2001 –

"A European Roadmap for Developing Accelerator Driven Systems (ADS)
for Nuclear Waste Incineration" published April 2001

Actively participates in working groups of NEA/OECD related to transmutation:

ADS – FR transmutation study, published 2002

Reliability of high power accelerators for ADS

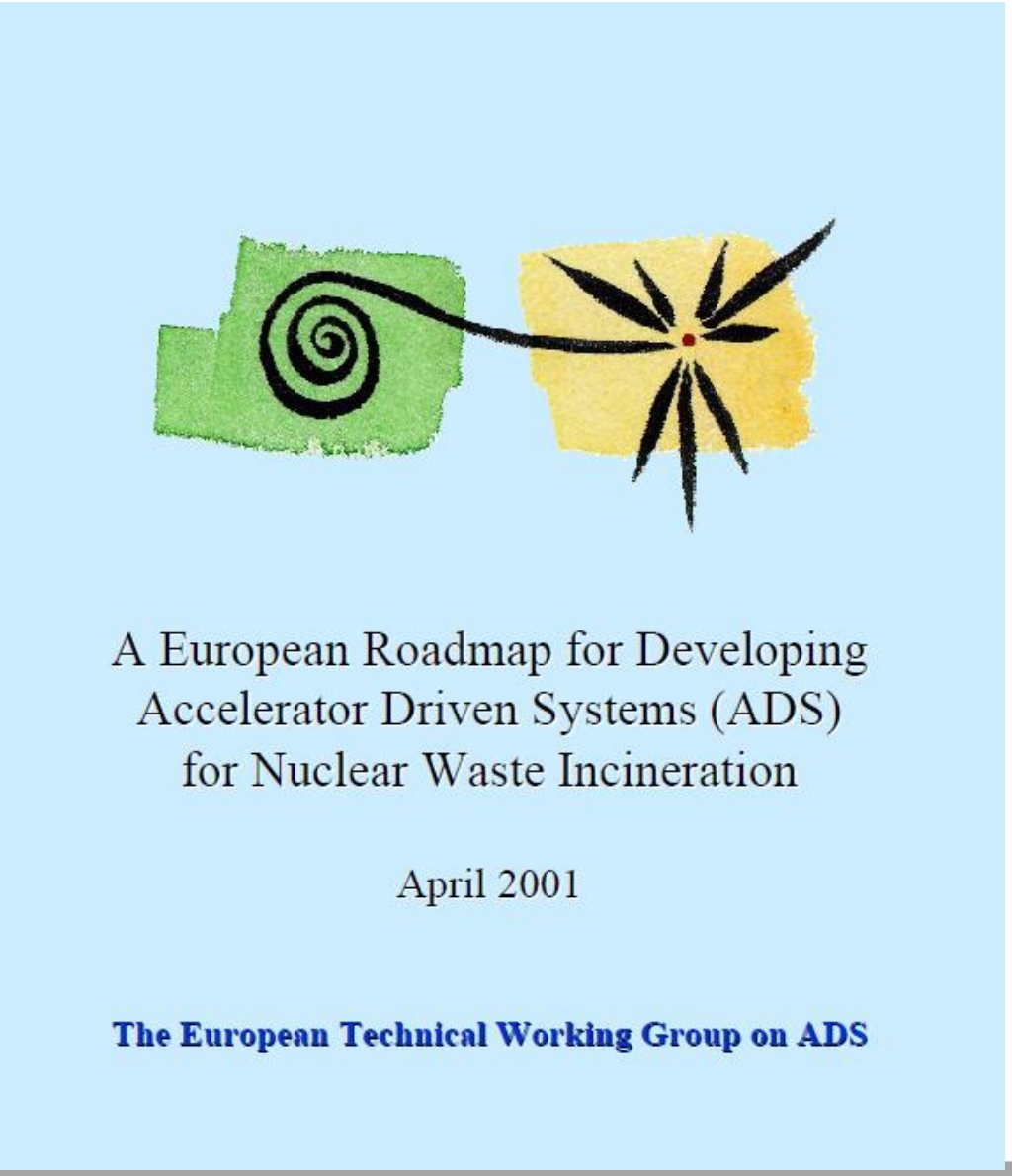
KTH participates in European Roadmapping Report. Published

Programme Committee of Acc/App01 Conference in Reno
International Scientific Review of Myrrha project
1 MW spallation target project successfully finished in Russia
Evaluates Korean transmutation programme

2002-

W. Gudowski in collaboration with IPPE and LANL managed to get spallation target shipped to US. This was the "heaviest/biggest" shipment of scientific equipment from Russia after 1991. Unfortunately US gets no funding for irradiation experiments at LANSCE and target sent tyo University of Nevada Las Vegas

A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration" published April 2001



How this technology was pulled out from the Russian military secrecy

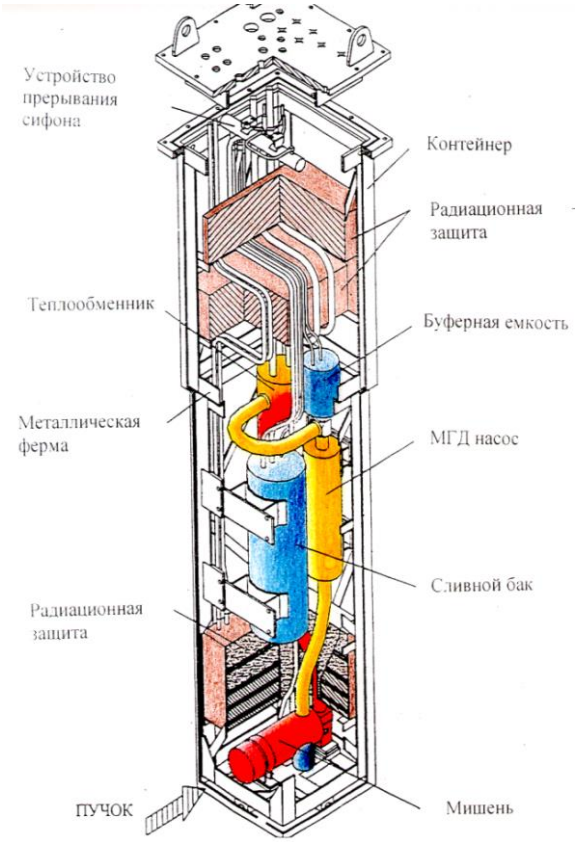
2002 –

Idea and pre-project of SAD experiment – SAD – Subcritical Assembly in Dubna

In coming years we managed to get a Private-Public model funding for 20 M$ experiment in Dubna but both DOE and EC got scared of embarquing into such cooperation. ISTC got unfortunately a clear message – stop after pre-conceptual design.

Development of HM coolant technology in ADS

1 MW pilot spallation neutron target (2002)

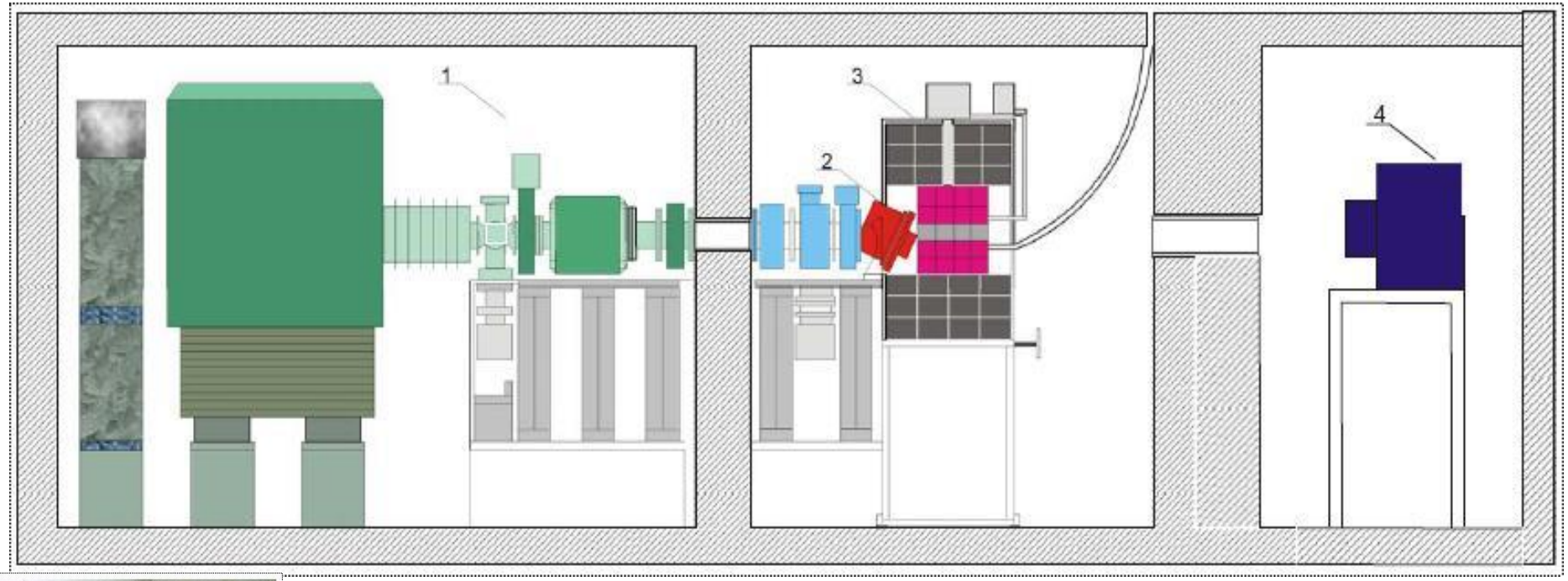


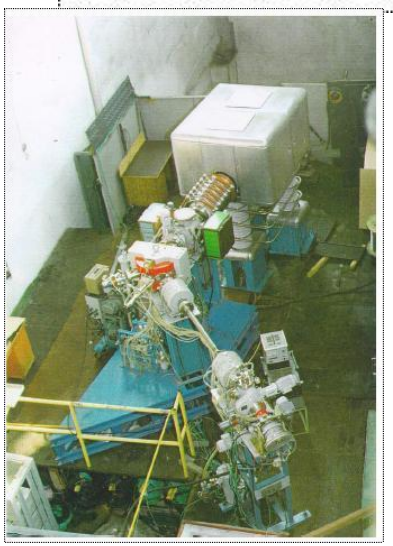
ОБЩИЙ ВИД МИШЕННОГО КОМПЛЕКСА

Target at Las Vegas

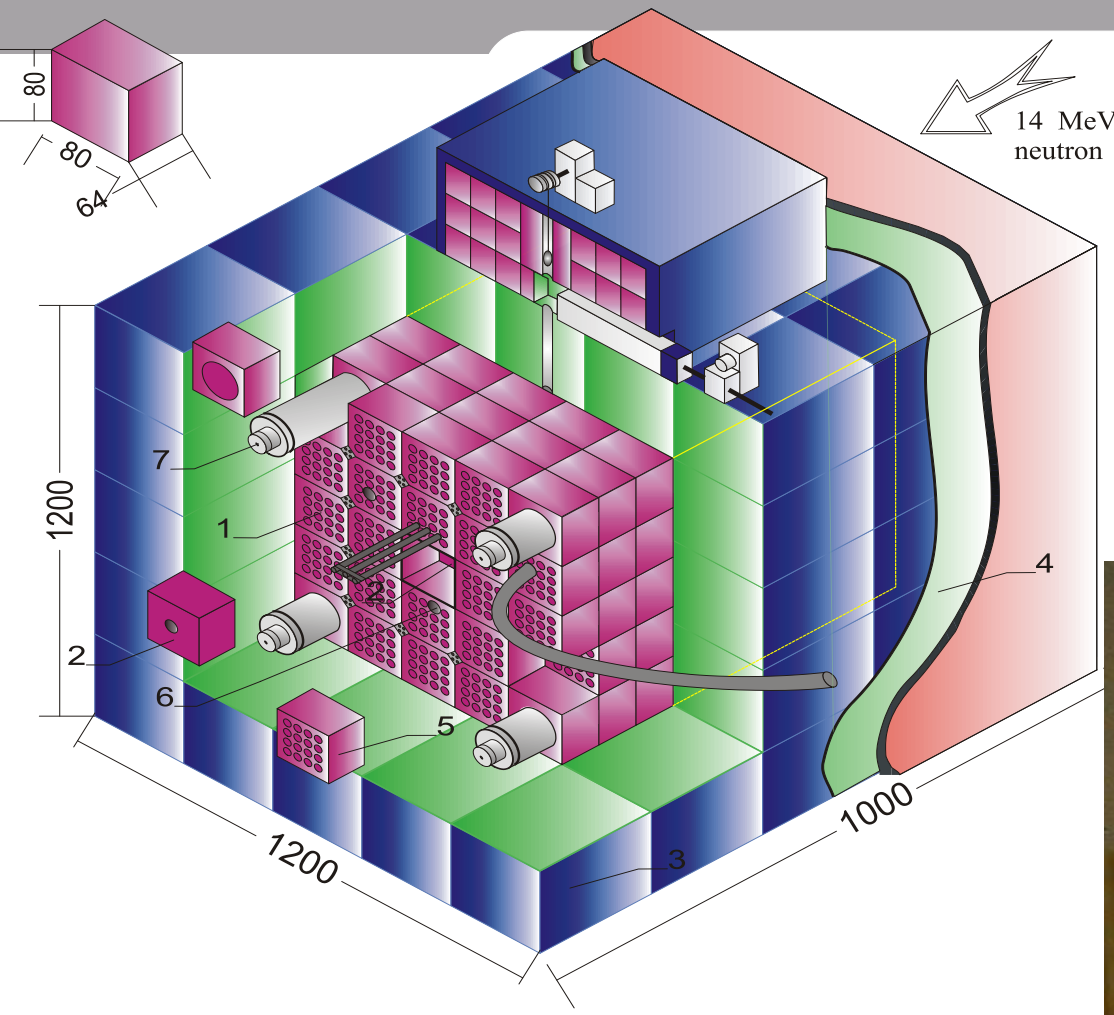
1 MW "MegaPie" target at PSI (2006)

#B070 - Yalina Subcritical Experiment in Minsk -2001



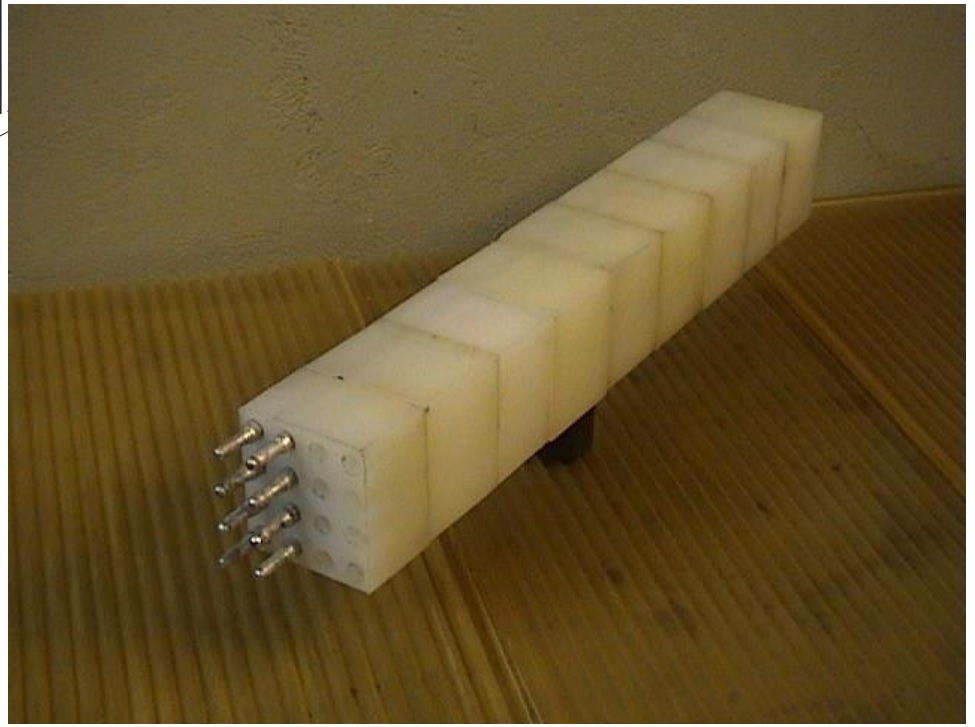


YALINA SUBCRITICAL FACILITY -2001 #B070



1 - core
2 - Pb target
3 - graphite reflector
4 - cadmium screen
5 - polyethylene block
6 - experimental channel
7 -detectors for neutron flux monitoring

Uranium-polyethylene assembly



General view of the YALINA fuel assembly.

Pb-Bi heavy metal coolant technology transfer

Pb-Bi Laboratory at IPPE - 1997

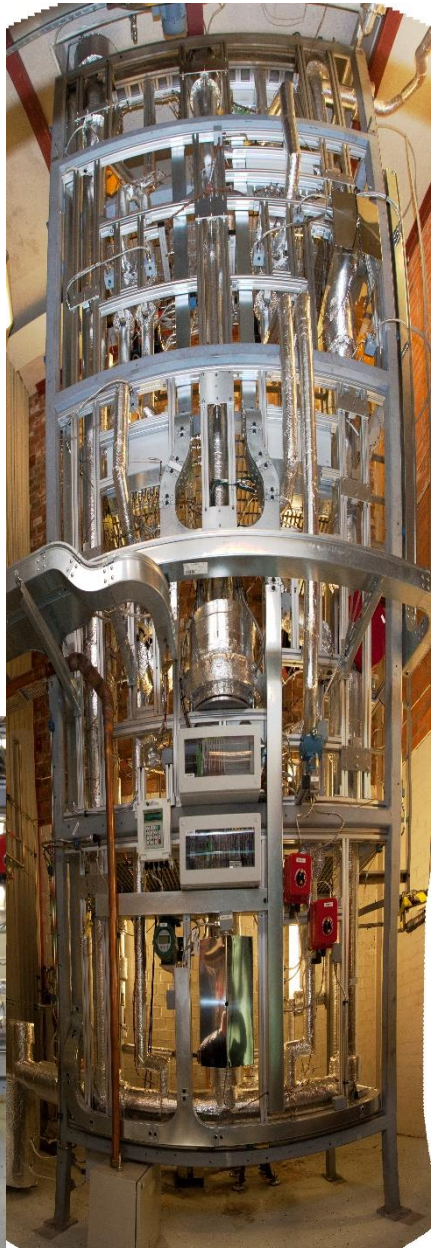
Kalla Pb-Bi Laboratory – FZK Karlsruhe – 2002

TALL loop at KTH - 2004

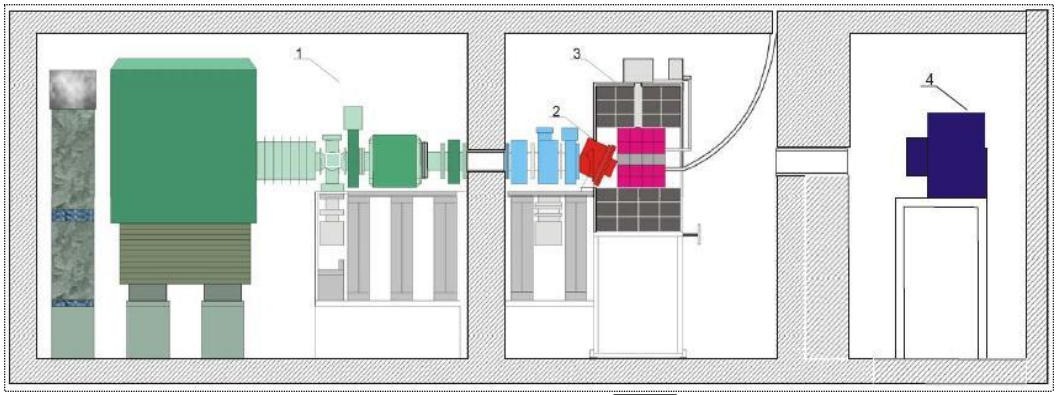
From TECLA to TALL 3D

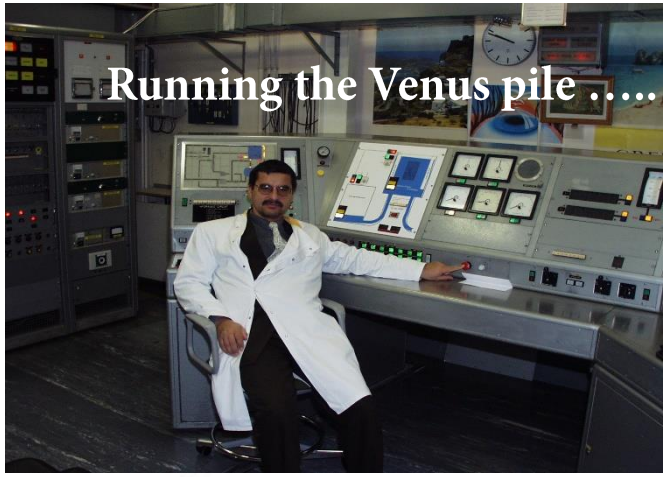
TALL-TECLA loop 2003

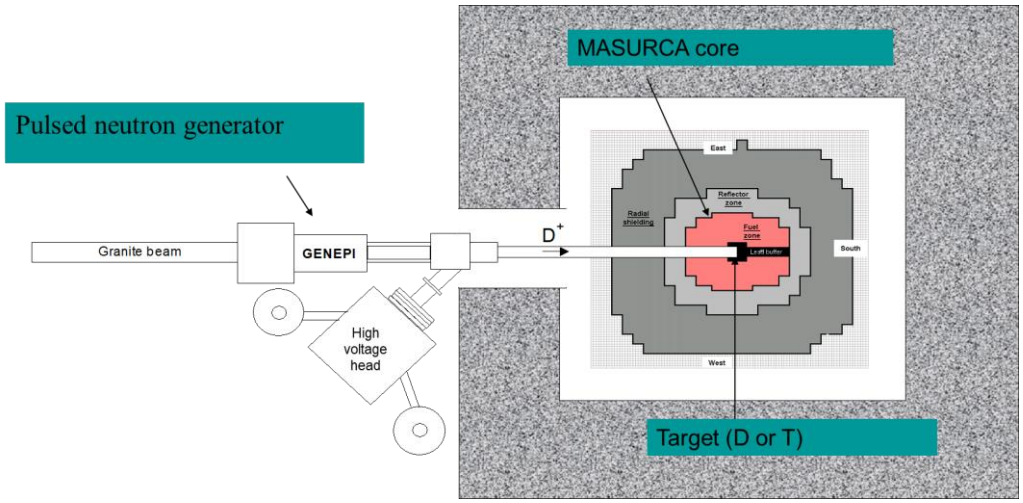
TALL3D-2016

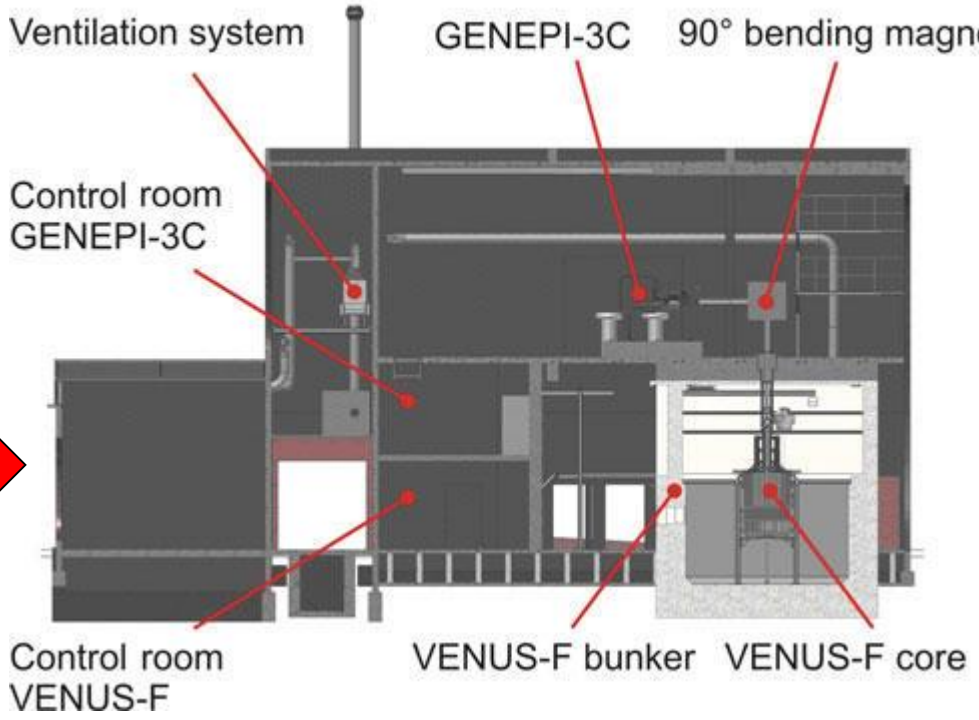


From Yalina to **Muse and** to GUINIVERE (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **Re**actor) or from SODIUM to Bismuth, Pb-Bi, Pb



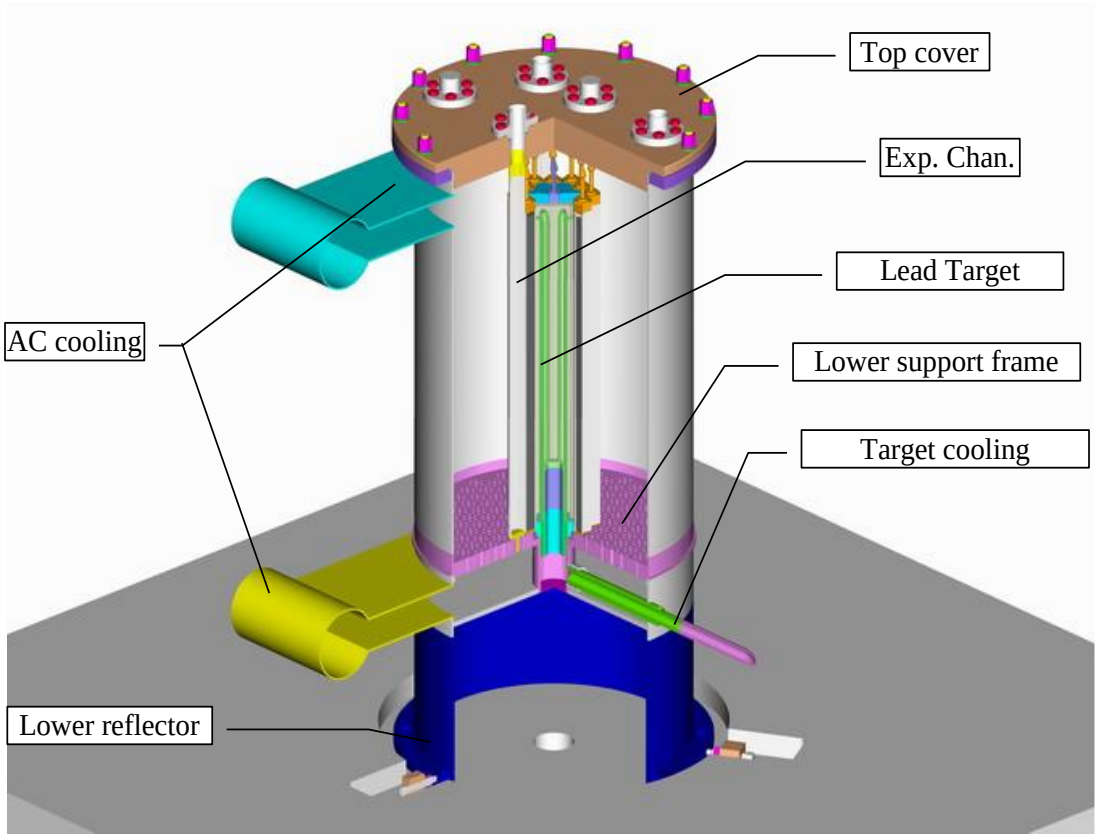




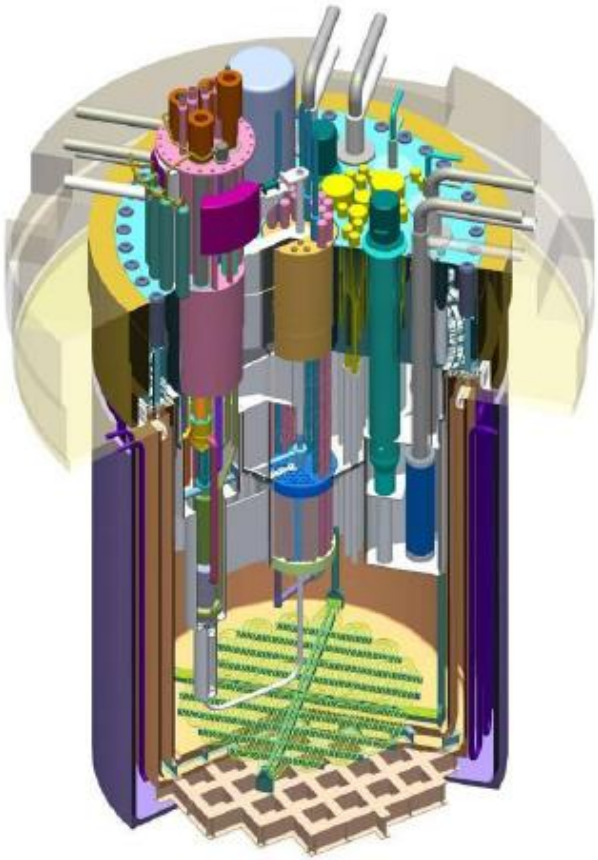


ISTC ADS Projects

SAD – Pre-conceptual design of Transmutation System – 2004-2005



Myrrha –Design of Transmutation/Irradiation System – 2016



Fathers of Pb-Bi/Pb technology for nuclear power applications!

Yuri Orlov

Viktor Orlov

That's it!

Waclaw Gudowski
waclaw.gudowski@ncbj.gov.pl

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