A Brief History of Aircraft Nuclear Propulsion

F. Polidoro, CISE2007

«Popular Science» 1951

«Popular Mechanics», April, 1957

DREAMING NUCLEAR ENERGY

Popular Mechanics Magazine

WRITTEN SO YOU CAN UNDERSTAND IT

Vol. 75 JANUARY, 1941 No. 1

The MIRACLE of U-235

By Dr. R. M. Langer

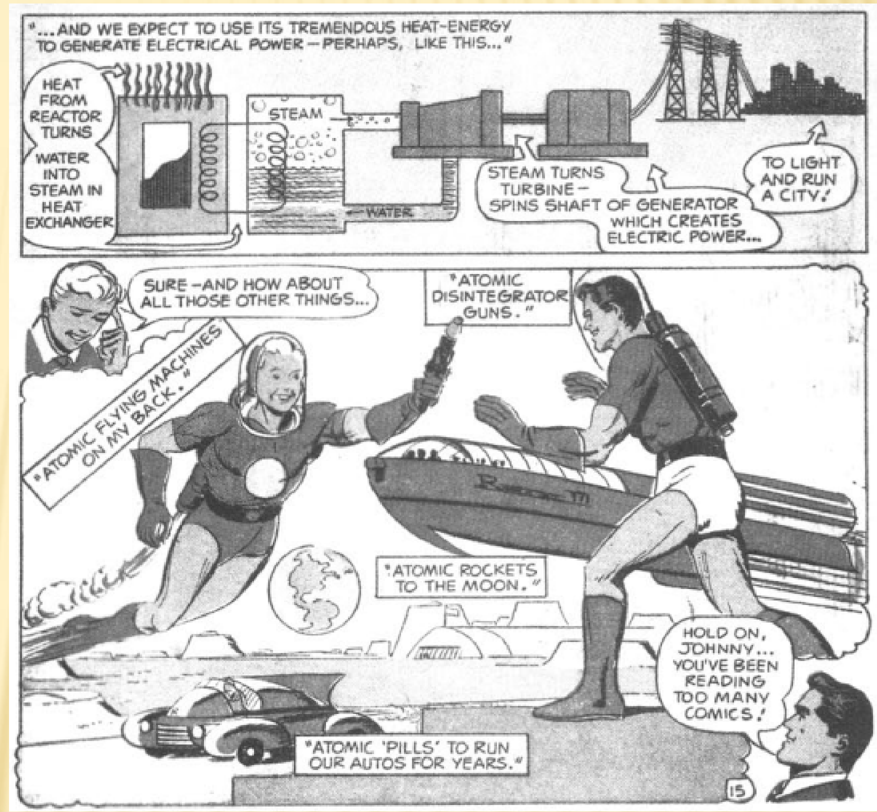
Editor's Note—One of the country's eminent physicists in this article paints a picture of the world as he visualizes it when U-235, a possible new source of power emerges from the laboratory. Dr. Langer, now at the California Institute of Technology, has been doing uranium atom research and has been connected with leading laboratories in this country and abroad.

SEVERAL months ago you read in Popular Mechanics that the secret of atomic power is close to solution and that possibly within a decade civilization will be using the tremendous amounts of energy contained in U-235, an isotope of uranium.

Since then additional research has opened up greater possibilities than ever. At first we thought that a heavy power plant weighing tons would be required to extract the power; now it appears that a pound or even a single ounce of

January 1941

The concept of a U-235 powered wing
«Popular Mechanics Magazine», January ,1941

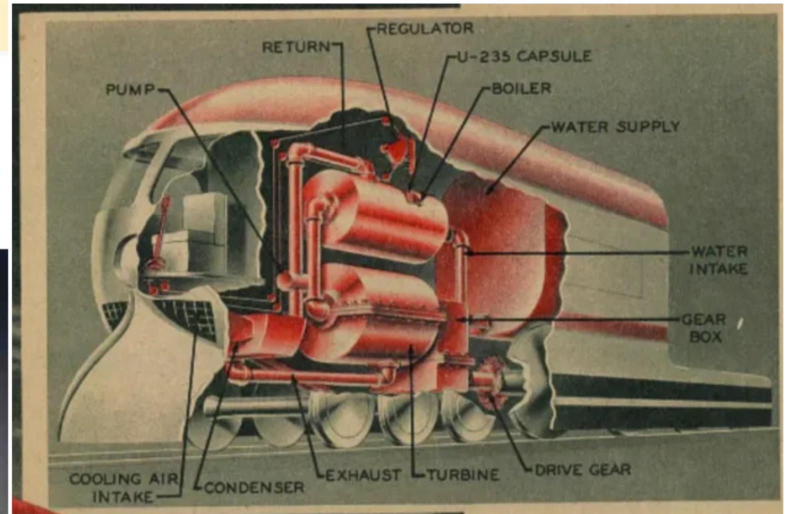


Comics, 1948

Nuclear-Powered Vehicle Concepts from the Mid-20th Century

Ford Nucleon, 1958

This 3/8th-sized scale model concept car was to be powered by a nuclear reactor (uranium fission-heated twin steam turbines) in the rear and was supposed to go 5,000 miles without refueling.



«Mechanix illustrated», August, 1955

Atomic Planes Are Closer Than You Think

High-payload atom-powered jet flying-boats within the next five to ten years: that's MI's prediction, based on a study of design trends and necessities.

By Frank Tinsley

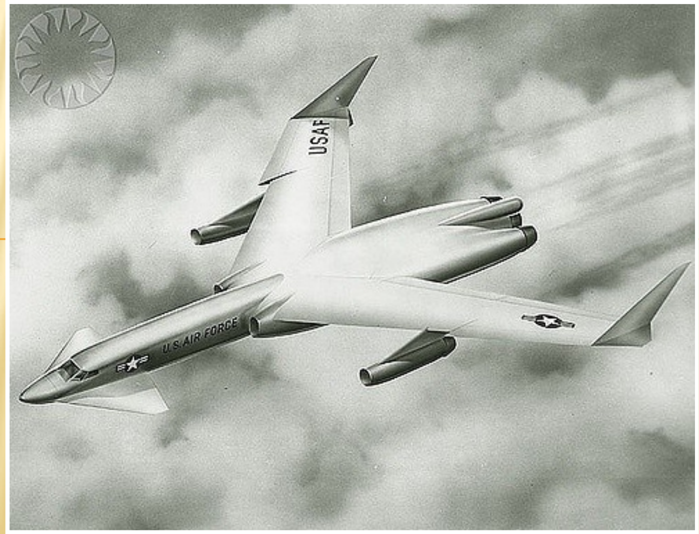
THE buckaroos of science are breaking the atom to harness at a fantastic rate. In just 15 short years, fission has grown from a super-secret equation whispered in a President's ear to a solidly established 14-billion dollar industry. The hectic stage of A- and H-bomb monopoly is fast giving way to a happier and less explosive phase of atomic development. Late last year Congress enacted the Atomic Energy Act of 1954; directing that the atom's neglected humanitarian potential be put to work "to promote world peace, promote the general welfare and increase the standard of living." Along with this, President Eisenhower launched his World Atoms-For-Peace Program to spur the exchange of knowledge and the rapid development of international

The idea of Aircraft Nuclear Propulsion

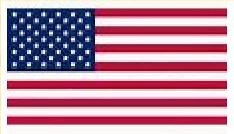
- In the United States, as early as 1942, Enrico Fermi envisioned the use of nuclear power to propel aircraft
- In June 1952, Aleksandr Kurchatov, chief designer of the Soviet atomic bomb, thought that a nuclear-powered aircraft could be built

Advantage

- Theoretically unlimited endurance and operating range (limited only by the crew)
- At the time of Cold-War this solution could provide an effective nuclear strategic deterrent



The nuclear-powered aircraft NX-2



PROGRAM

- The **Aircraft Nuclear Propulsion** (ANP) program and the preceding **Nuclear Energy for the Propulsion of Aircraft** (NEPA) project - initiated on 1946 - worked to develop a nuclear propulsion system for aircraft of unlimited range

- Since 1951 the project was transferred to the joint **Atomic Energy Commission** (AEC)/**USAF ANP**.

- The USAF focused on two different systems for nuclear-powered jet engines:

  - **Direct air-cycle** concept developed by General Electric

  - **Indirect air-cycle** concept assigned to Pratt & Whitney

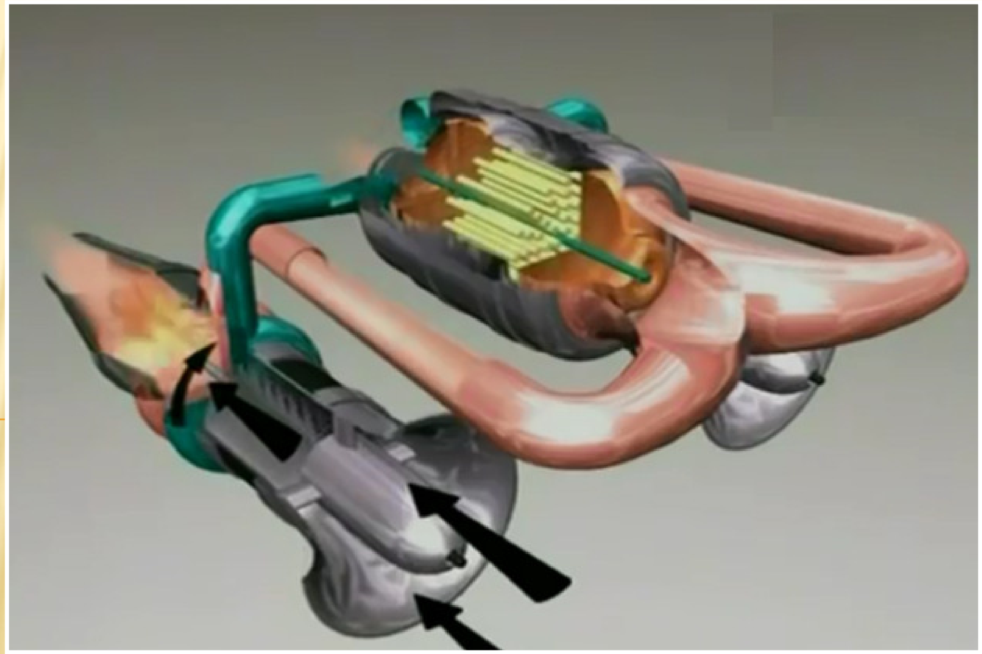
- The program was intended to develop an aircraft powered by nuclear energy within **1960**

Direct air-cycle (GE design)

Air enters through the compressor, is forced into the reactor and heated by fuel elements. After passing through the turbine, where energy is extracted to drive the compressor, the heated air is expelled at heigh velocity (temperature) through the exaust nozzle

Advantages: more simple, reliable, high-performance, fast system to develop (no additional rotating components)

Drawbacks: potentially contaminated exaust air («dirty system»)

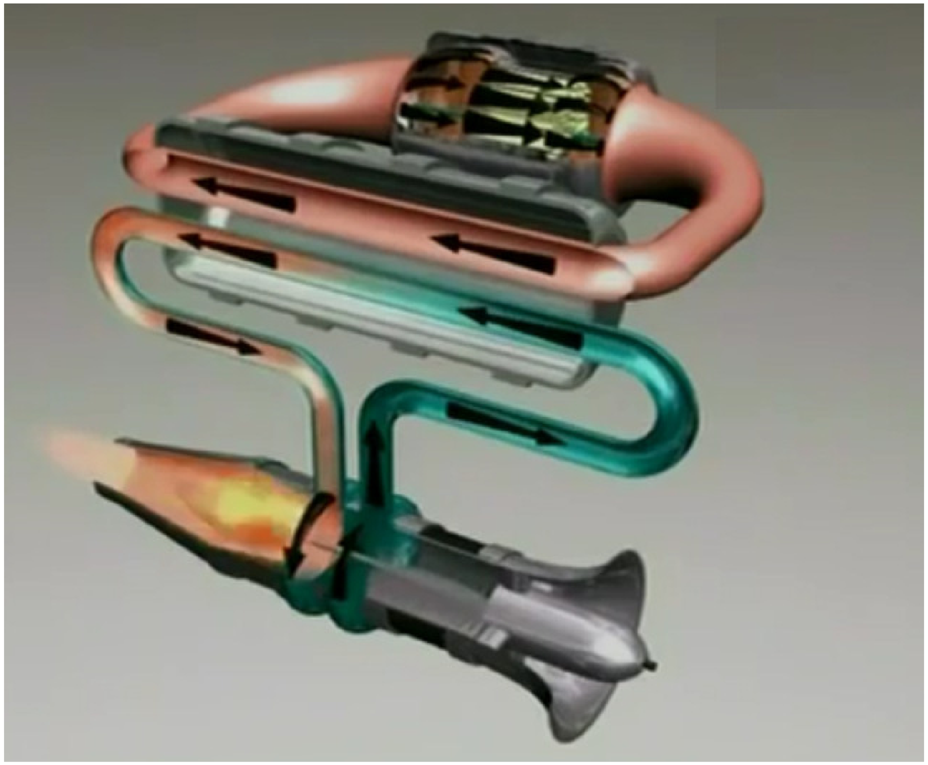


Indirect air-cycle (Pratt & Whitney design)

Air instead to flow through the core, it passes through a heat exchanger. The heat generated by the reactor is carried by liquid metal or highly pressurized water to the heat exchenger, where air is heated and then expelled

Advantages: less radioactive pollution («clean system»)

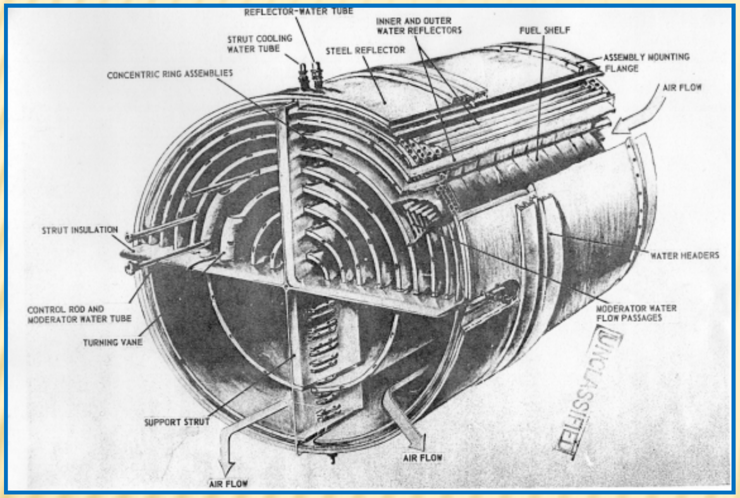
Drawbacks: heavy and complicated system to develop, lower efficiency



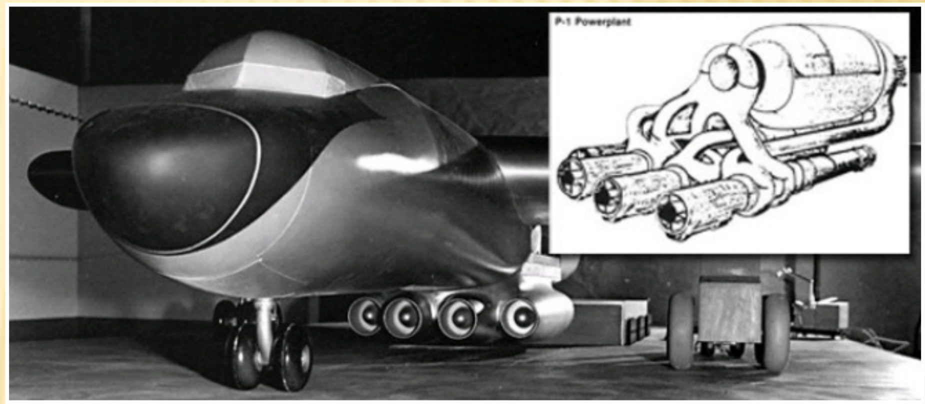
Early works (1951-1954)

P1-power plant

- One large reactor (R1-reactor) powering 4-turbojet engines mounted under the fuselage of B-36 bomber



The R-1 reactor

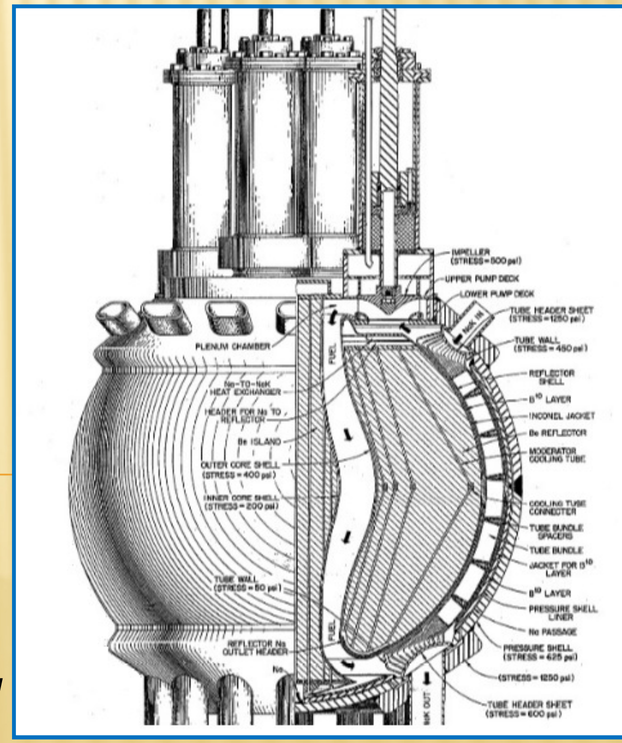


The P1-power plant mockup

- R1-reactor: 9 annular concentric air passages containing fuel elements (UO_2, SS as cladding, water as moderator)
- Development approved in 1952, ground tests scheduled for 1954 with flight in 1957. Program cancelled in 1953
- Most of the equipments and control rod systems used in later experiments

Aircraft Reactor Test (Fireball)

- Developed at Oak Ridge National Lab. (ORNL) as follow-up of the Aircraft Reactor Experiment (ARE)
- Molten salt reactor operating at 60 MW (indirect air-cycle)
- Advantages: high-temperature, high-power density reactor operating at low pressure (low vapour pressure of molten salt)
- Fuel: molten flouride salt (NaF-ZrF_4-UF_4) with 93.4% ^{235}U
- Moderator: BeO
- Coolant: liquid sodium-potassium eutectic (NaK)
- NaK used to carry heat to turbojet engine
- Studies used to develop the MSR technology

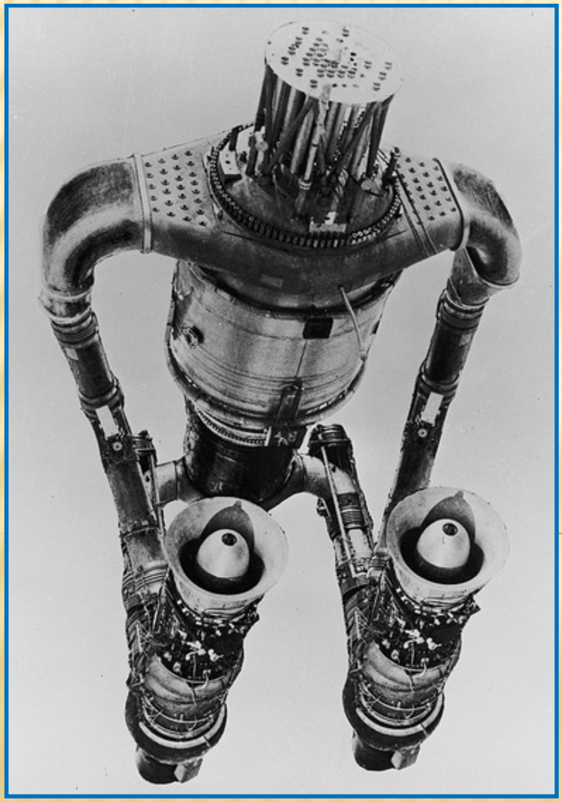


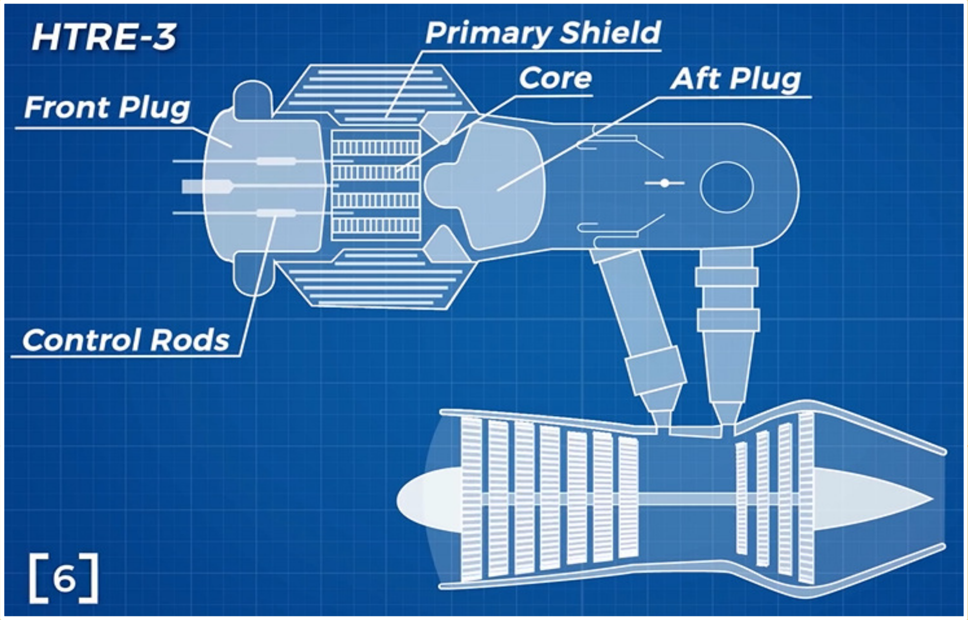
Section view of Fireball

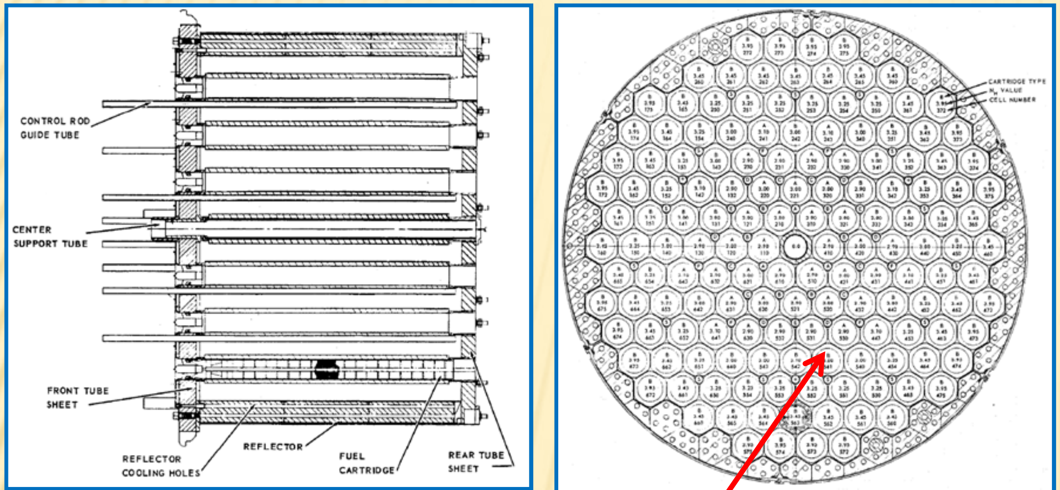
HTRE experiments (1956 – 1959)

In 1956 General Electric developed a reactor test assembly known as Heat Transfer Reactor Experiment (HTRE series 1-2 and 3) in the direct-cycle configuration

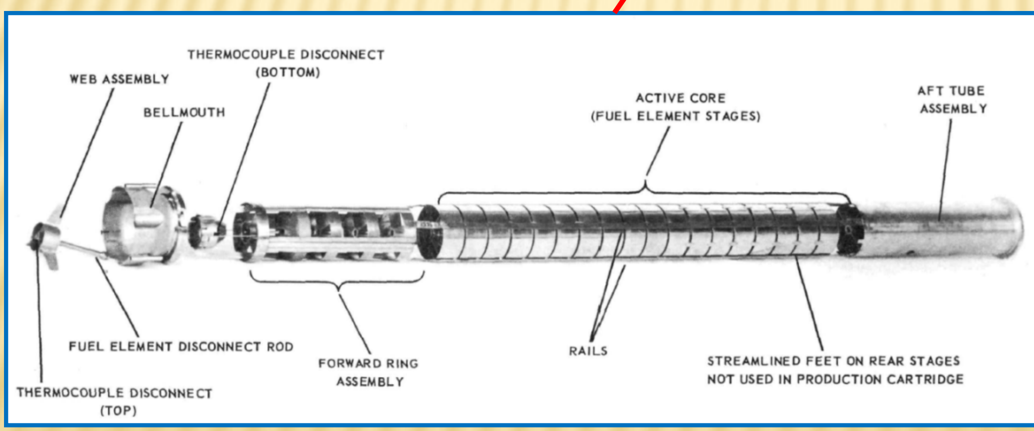
- HTRE-3 dimensioned to provide flight propulsion (power level and airflow chosen to be characteristic of flight service)
- HTRE-3 became the first reactor to start a turbojet engine







Core Assembly: lateral and front views



Fuel cartridge assembly

Core design

Configuration: hexag. array of 151 cells

Fuel: UO_2 in a matrix Ni-Cr

^{235}U enrichment: 93.2% (~ 177 kg)

Moderator: ZrH_2 (hydrided zirconium)

Reflector: beryllium

Structural material: Inconel-X

Control rods : Eu_2O_3 (Europium oxide)

Core coolant: air

Over-all length: 1.1 m

Active length: 0.8 m

Nominal diameter: 1.3 m

Thermal output: 35 MW

Shield assembly

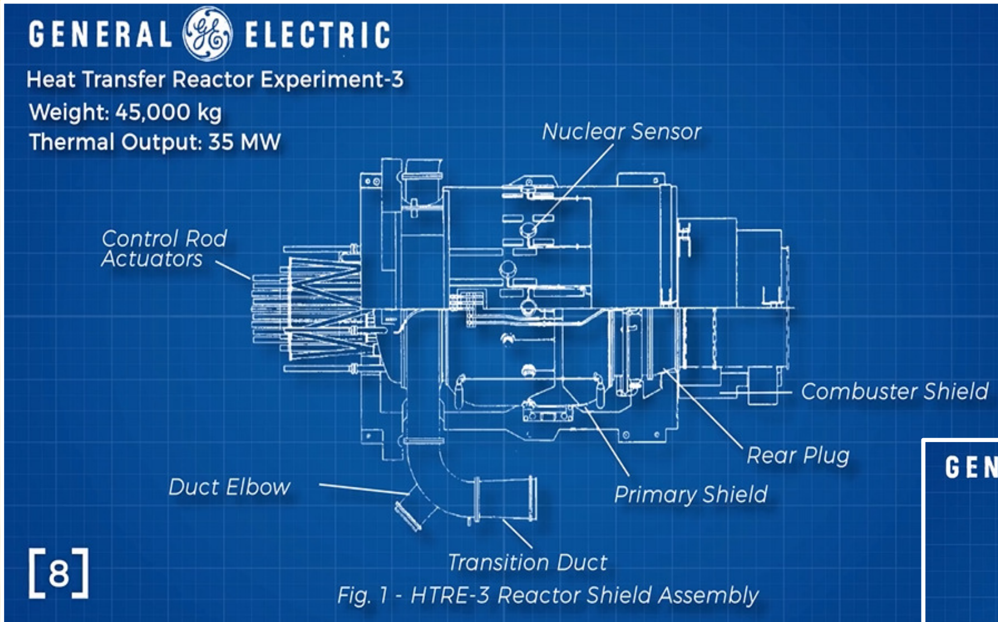


Fig. 1 - HTRE-3 Reactor Shield Assembly

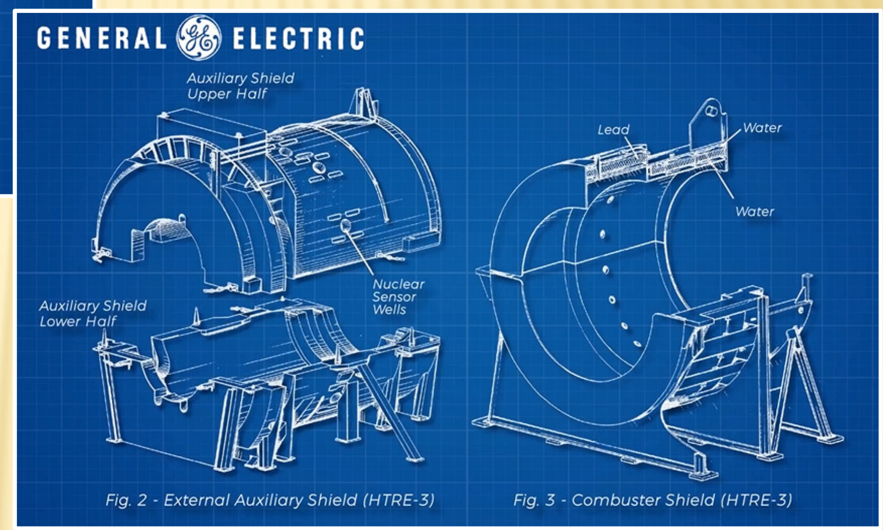


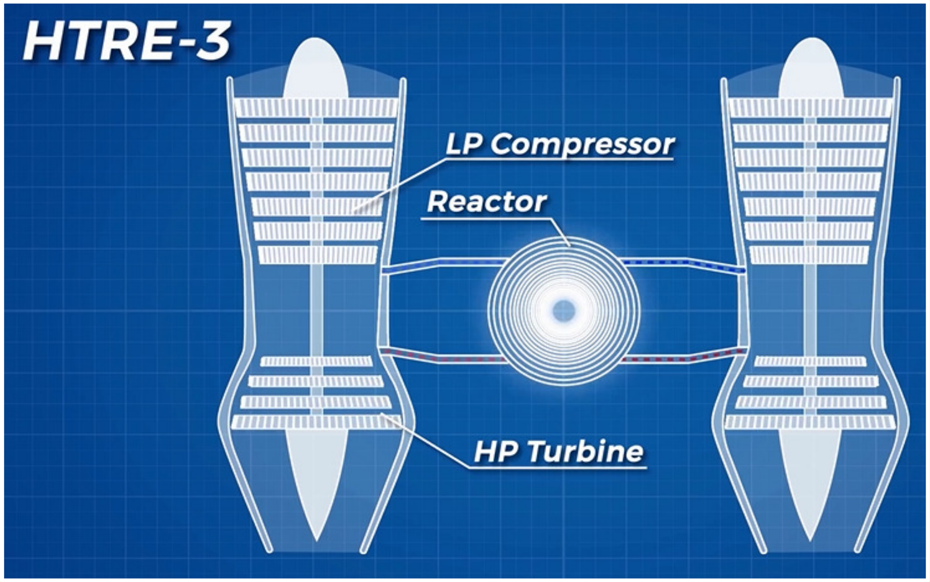
Fig. 2 - External Auxiliary Shield (HTRE-3)
Fig. 3 - Combuster Shield (HTRE-3)

<u>Primary shield</u> (simulating a fight-type shield structure)

- Borated H_2O (50 cm thick) for neutron in an Inconel-X SS shell
- Pb slabs for gamma radiation

<u>External auxiliary shield</u> (for test requirements on dose)

- H_2O in a SS shell surrounding the primary shield



Engine

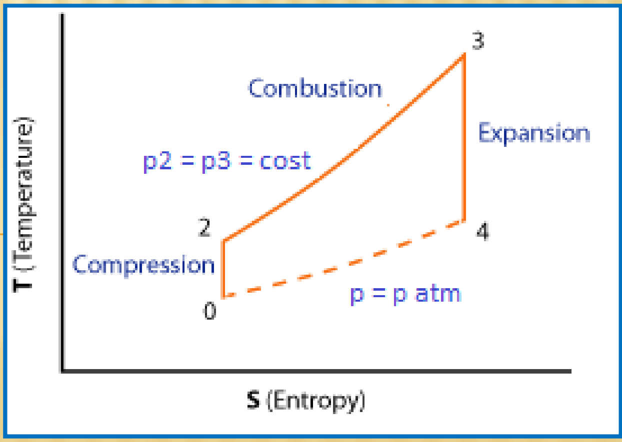
Type: X39-5
Quantity 2

Test performance

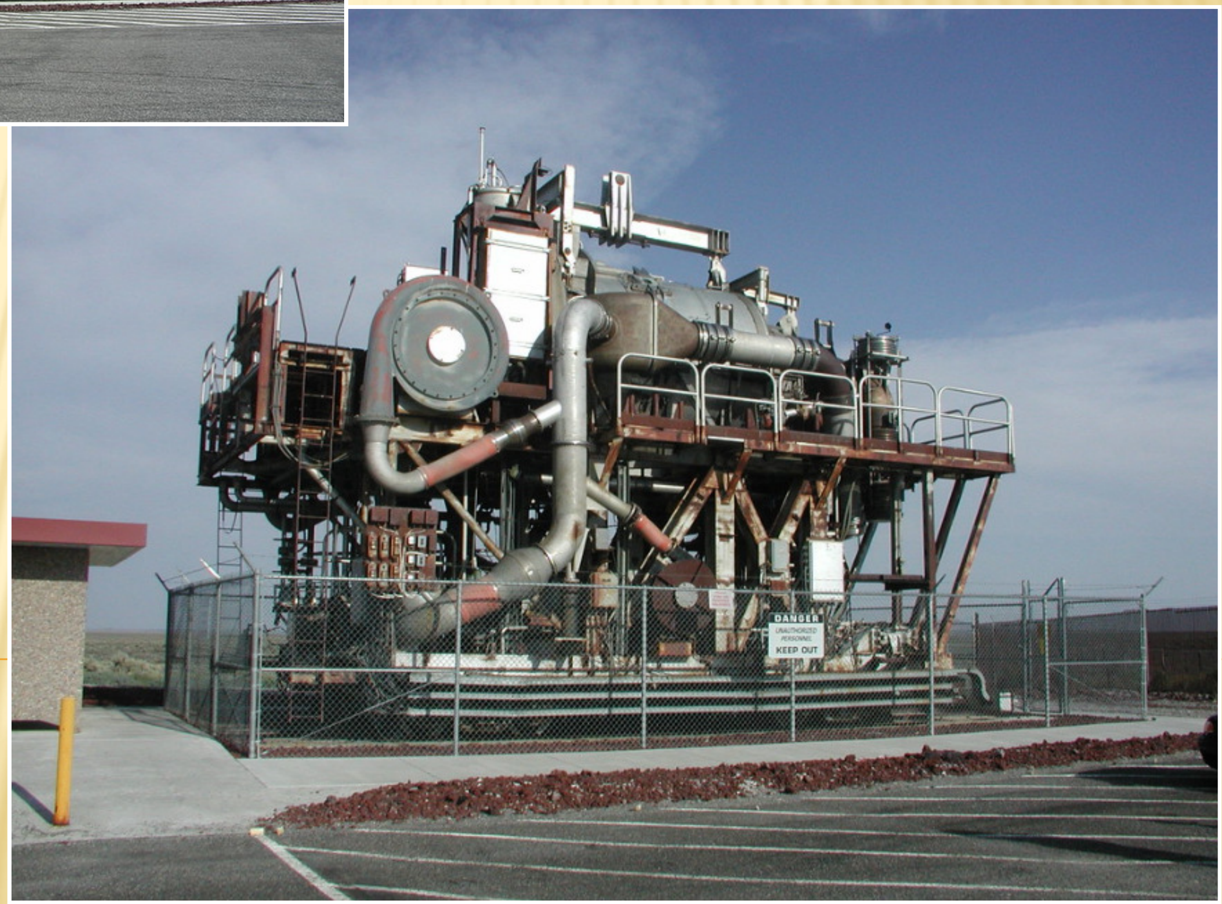
It operated at full power nearly continuously for 126 hours

Thermodynamic performance

Compressor discharge temperature	196	℃	②
Compressor discharge pressure	3.7	bar	②
Compressor airflow (2 engines)	57.1	kg/s	
Reactor airflow	55.3	kg/s	
Core inlet air pressure	3.4	bar	
Fuel element exit air temperature	768	℃	
Reactor discharge temperature	721	℃	③
Turbine inlet pressure	2.9	bar	③
Pressure drop compressor → turbine	~ 0.8	bar	
Maximum turbine inlet temperature	871	℃	



Idaho National Laboratory: HTRE-2 (left) and HTRE-3 (right) test facilities



HTRE-3 test facility

XMA – 1 nuclear turbojet (1955 – 1959)

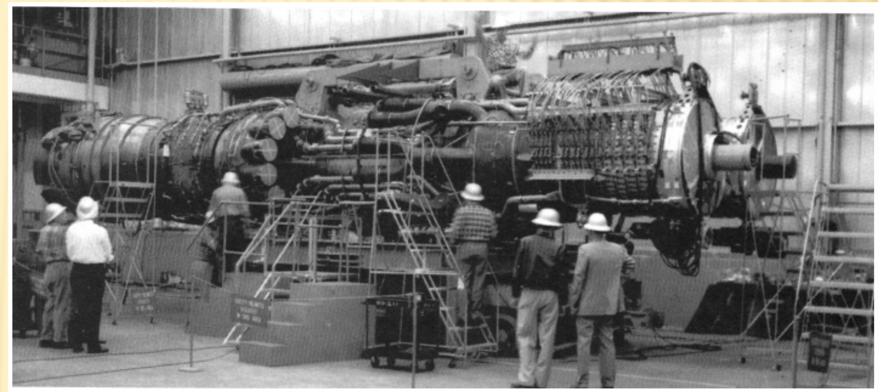
- Two GE-X211 turbo machines coupled to one reactor and shield assembly

- XMA – 1A (early design): as HTRE-3 reactor. Dual mode operation:

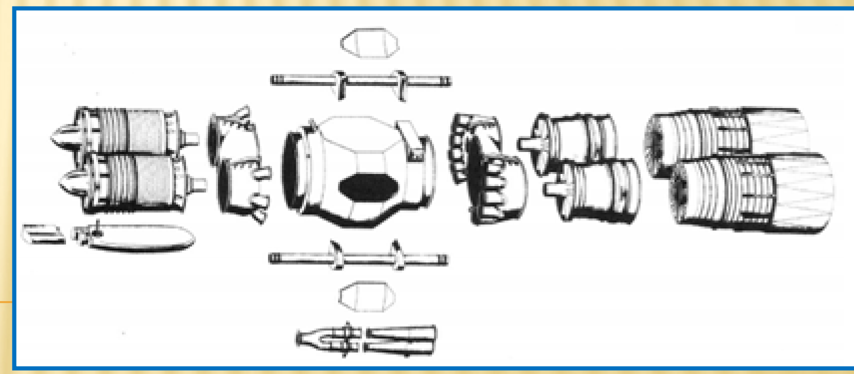
  - nuclear flow-path

  - chemical flow-path (or a combination of them)

- XMA – 1C (advanced design): improved performance by using ceramic fuels (as in HTRE-2)



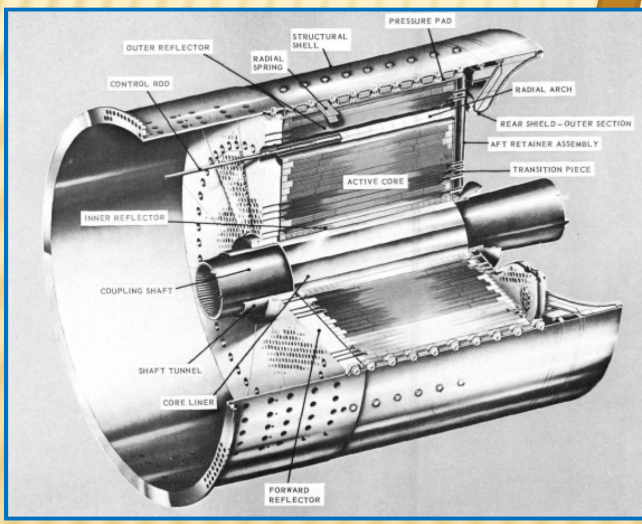
The nuclear engine in build up phase

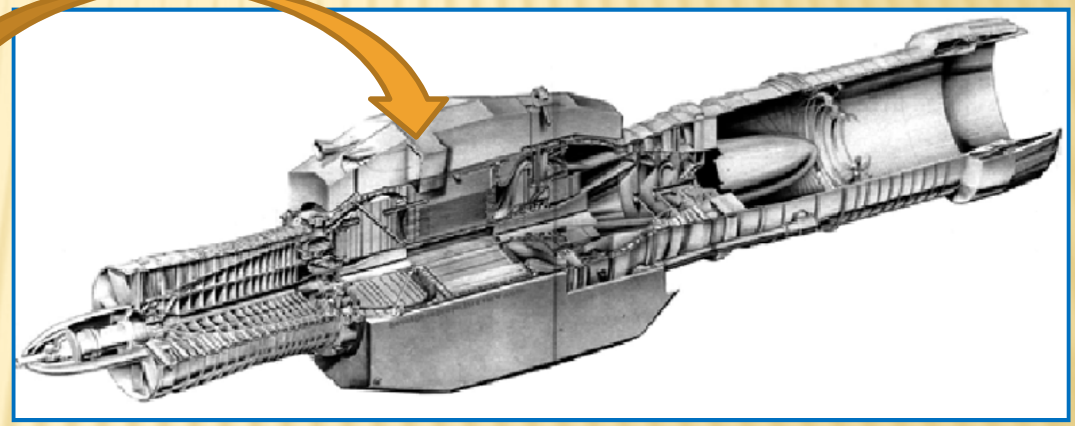


Twin nuclear turbojets configuration

XNJ 140E nuclear turbojet (1960-1962)

- Designed to use a single GE-X211 turbojet
- Direct-cycle (power: 121 MW, engine life potential: 1000 h, speed: 0.8 Mach @ 10500 m)
- Reactor: BeO + UO_2 (93% in ^{235}U) + Y_2O_3 (yttrium oxide) to limit fuel conversion to higher states of oxidation

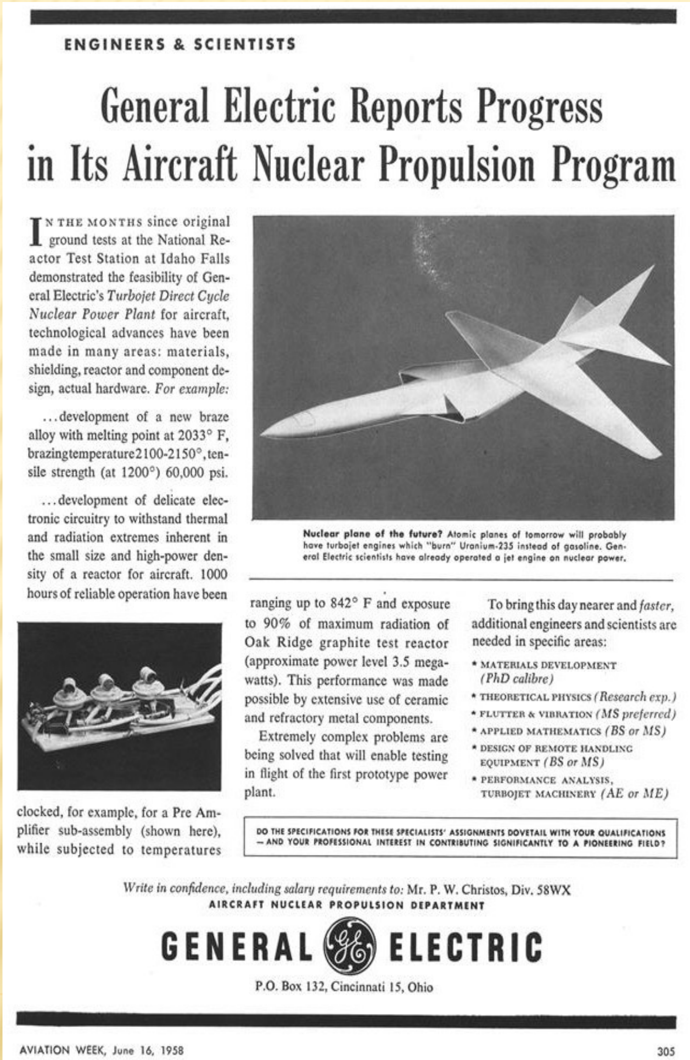




Section view of XNJ 140E nuclear turbojet

- Ground test scheduled for December 1962, with flight testing to begin on Convair NX-2 in 1965

Open literature on GE projects (end ‘50 – beginning ‘60)



ENGINEERS & SCIENTISTS

General Electric Reports Progress in Its Aircraft Nuclear Propulsion Program

IN THE MONTHS since original ground tests at the National Reactor Test Station at Idaho Falls demonstrated the feasibility of General Electric's *Turbojet Direct Cycle Nuclear Power Plant* for aircraft, technological advances have been made in many areas: materials, shielding, reactor and component design, actual hardware. *For example:*

...development of a new braze alloy with melting point at 2033° F, brazingtemperature2100-2150°, tensile strength (at 1200°) 60,000 psi.

...development of delicate electronic circuitry to withstand thermal and radiation extremes inherent in the small size and high-power density of a reactor for aircraft. 1000 hours of reliable operation have been clocked, for example, for a Pre Amplifier sub-assembly (shown here), while subjected to temperatures ranging up to 842° F and exposure to 90% of maximum radiation of Oak Ridge graphite test reactor (approximate power level 3.5 megawatts). This performance was made possible by extensive use of ceramic and refractory metal components.

Extremely complex problems are being solved that will enable testing in flight of the first prototype power plant.

Nuclear plane of the future? Atomic planes of tomorrow will probably have turbojet engines which "burn" Uranium-235 instead of gasoline. General Electric scientists have already operated a jet engine on nuclear power.

To bring this day nearer and *faster*, additional engineers and scientists are needed in specific areas:

- MATERIALS DEVELOPMENT *(PhD calibre)*
- THEORETICAL PHYSICS *(Research exp.)*
- FLUTTER & VIBRATION *(MS preferred)*
- APPLIED MATHEMATICS *(BS or MS)*
- DESIGN OF REMOTE HANDLING EQUIPMENT *(BS or MS)*
- PERFORMANCE ANALYSIS, TURBOJET MACHINERY *(AE or ME)*

DO THE SPECIFICATIONS FOR THESE SPECIALISTS' ASSIGNMENTS DOVETAIL WITH YOUR QUALIFICATIONS — AND YOUR PROFESSIONAL INTEREST IN CONTRIBUTING SIGNIFICANTLY TO A PIONEERING FIELD?

Write in confidence, including salary requirements to: Mr. P. W. Christos, Div. 58WX
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GENERAL ELECTRIC

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AVIATION WEEK, June 16, 1958 305

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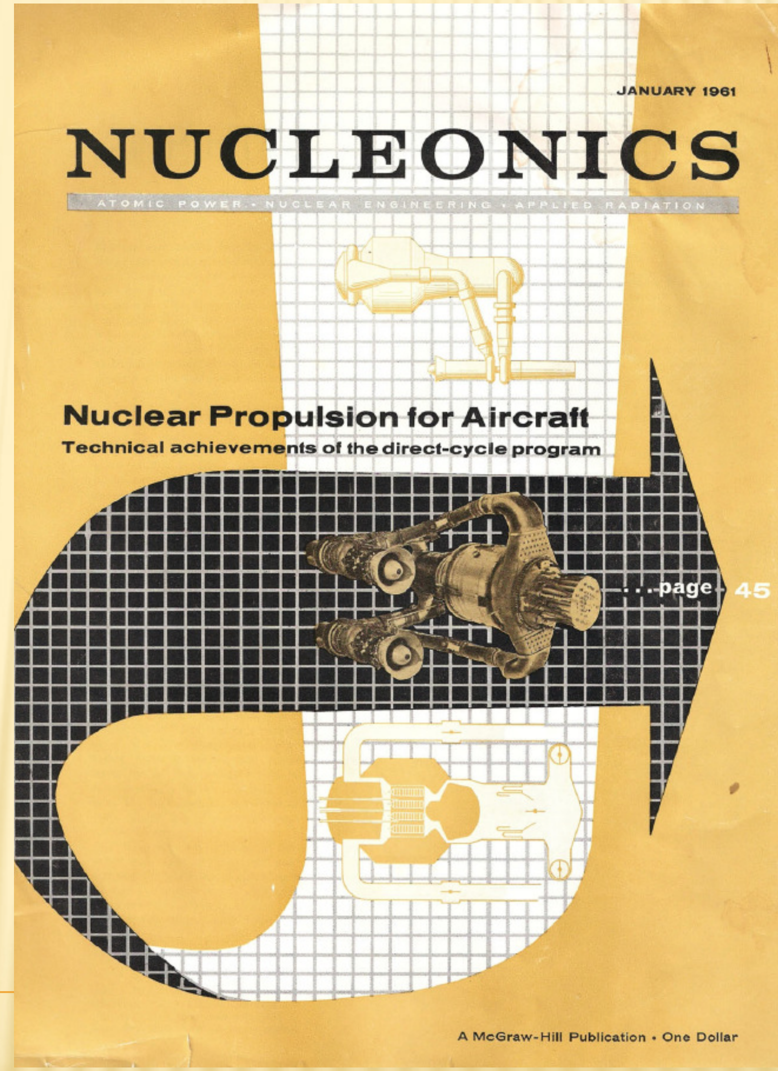


«Nucleonics» January, 1961

Most of technical documents: “Confidential-Restricted Data”. Unclassified since ‘70

Flight tests

- Necessary to get adequate shielding and nuclear processing data
- The Convair B-36 (renamed NB-36H "Crusader") chosen for its huge fuselage (49 m) and great payload capacity

The NB-36H in a test flight, shadowed by a Boeing B-50 *Superfortress*

Type: nuclear power strategic bomber

Power: 6 x 3800-hp piston engines, 4 turbojets, 1 R-1 reactor (1MW)

Maximum speed: 616 km/h

Endurance: theoretically unlimited

Crew: 5 (including 2 nuclear engineers)

Range: theoretically unlimited

Weight: empty 102 tons, loaded 164 tons

Armaments: nuclear bombs

Dimensions: span 69.60 m
length 49.00 m
height 14.08 m
wing area 443.3 m^2

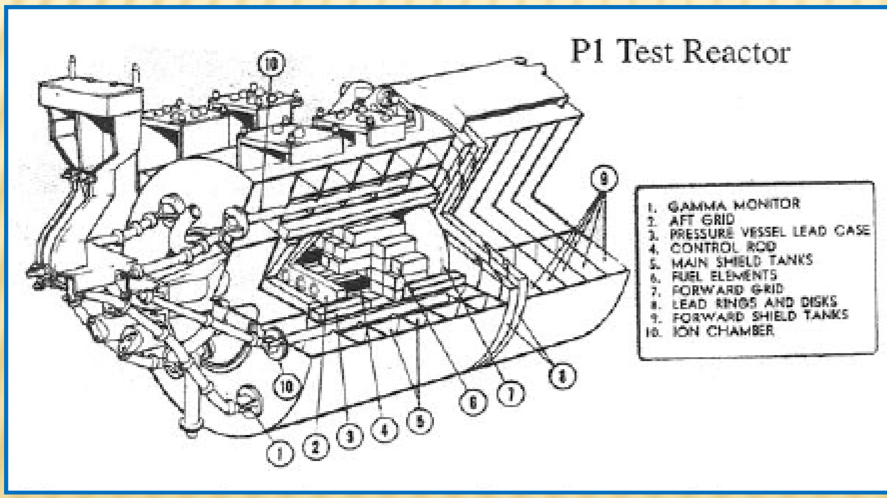
In September 1955, the Convair NB-36H bomber with 1 MW reactor had first test flight (reactor NOT used for propulsion but to test the effects of a nuclear reactor in a flying aircraft)

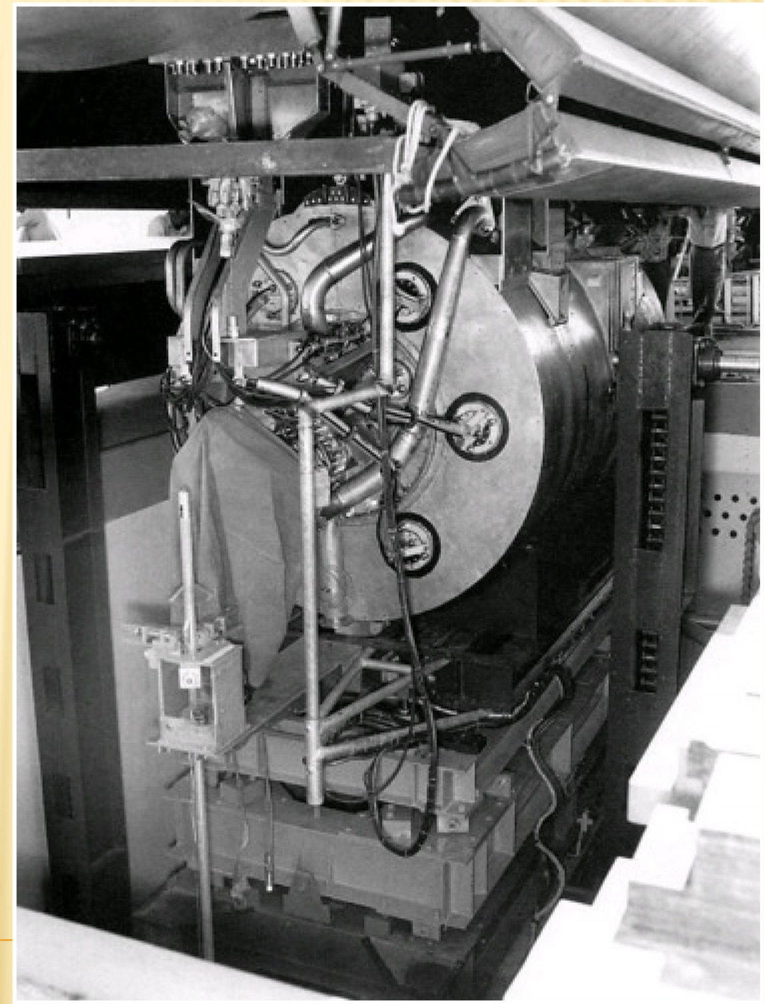
Control panel of the nuclear instrumentations

- 47 flight tests in 2 years
- Reactor powered up over the New Mexico desert

P1 Test reactor

- Thermal water-cooled reactor
- Fuel: enriched uranium
- Radiation shield: water
- Power : 1 MW at the altitudes up to 40.000 ft
- Reactor heat carried off through heat exchangers cooled by air



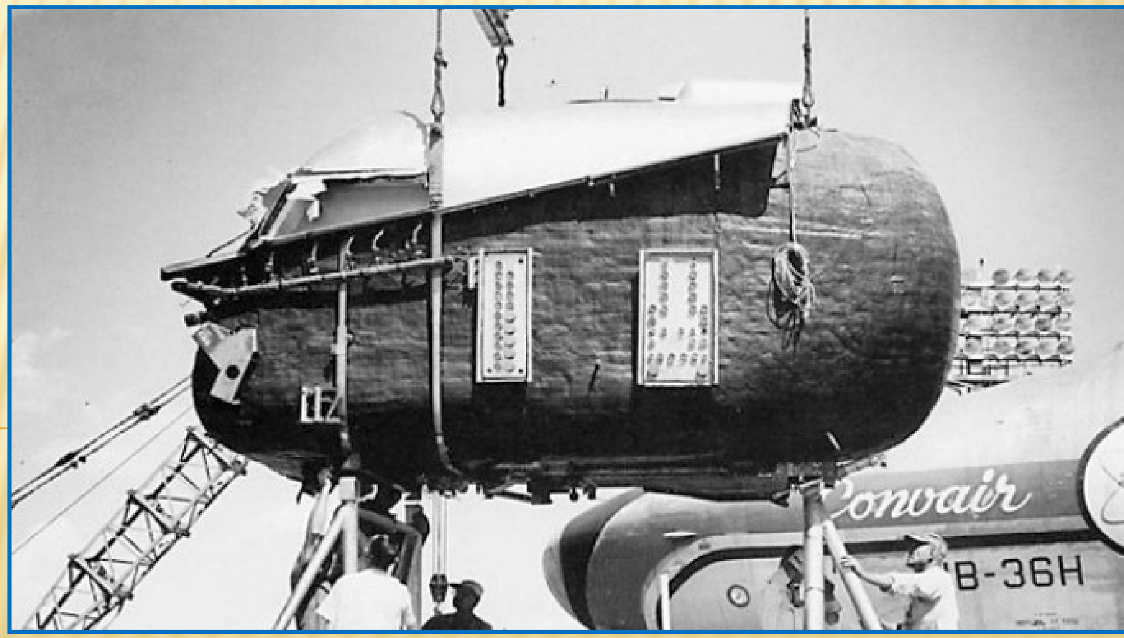


The 1MW (20 tons) reactor installed in the bomb-bay

- Reactor loaded and unloaded for each flight

Main modifications of B-36 aircraft:

- Original crew and avionics cabin replaced by a massive 11 ton structure lined with lead (up to 6 cm thick) and rubber (up to 43 cm thick)
- Additional lead shield of 3.6 ton installed in the center of fuselage in front of reactor
- Only pilots could see outside through a combination of leaded glass and Plexiglas 24 cm thick



Shielded cockpit installed in the Convair NB-3H

Convair's successful flight test program terminated in March 1957

Main concerns:

- Risk of accidents which would have caused the release of fission products

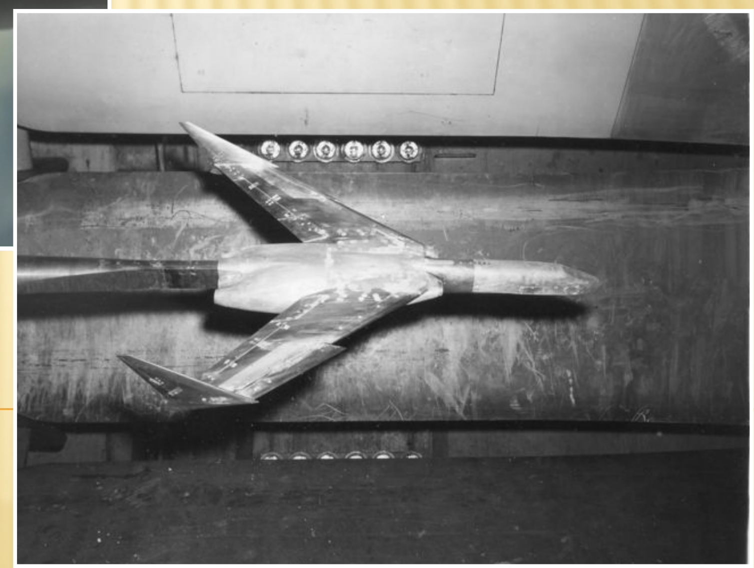
  During test flights an Air Force transport (B-50 Superfortress) also accompanied the aircraft carrying a team of soldiers/paramedics who could parachute to the ground to isolate and monitor any area where the aircraft could crash in case of accident

- Exposure to radiation for crew and ground personnel

Convair NX-2 bomber prototype

Designed to be powered by 2 XMA-1A reactor jet engines with a flight-range of around 500.000 miles (800.000 km!).

It was supposed to fly in 1963, with nuclear nuclear-powered flight by 1965



Test of Conavair NX-2 model in a 5 m transonic tunnel

Program cancellation

- Studies on nuclear propulsion aircraft - initiated in 1946 - continued untill the entire program was cancelled in March 1961 under Kennedy president.
- The total cost of the program was about $1 billion.

Main reasons:

- Development of intercontinental ballistic missiles
- Available of technology for on-flight aircraft refueling
- Development of nuclear powered submarines able to lunch ballistic missiles (Polaris A-1 system, 1960)

Movie: «The American's Plan for Nuclear Powered Planes» [11:28]

Movie: "Convair NB-36H "Crusader" Progress Report – 1956" [08:33]

PROGRAM

Tupolev Tu-95 LAL

Soviets Flight Testing Nuclear Bomber

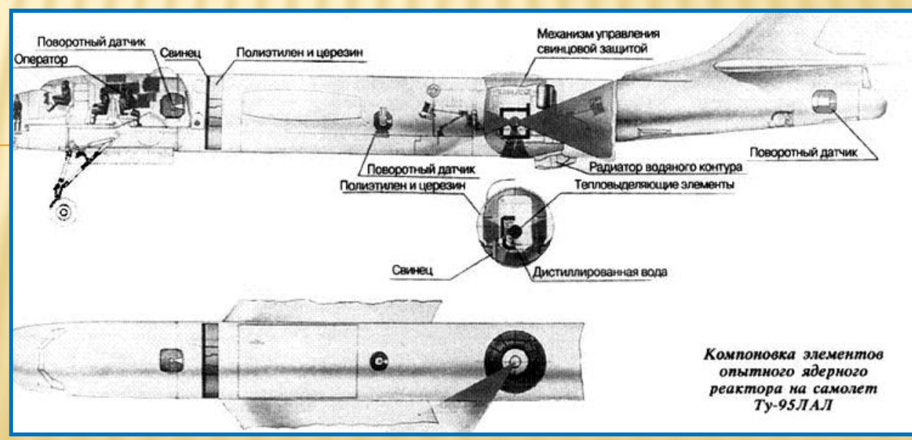
Washington- A nuclear-powered bomber is being flight tested in the Soviet Union.

Completed about six months ago, this aircraft has been flying in the Moscow area for at least two months. It has been observed both in flight and on the ground by a wide variety of foreign observers from Communist and non-Communist countries. In its initial flight testing, the new aircraft is powered by a combination of nuclear and conventinal turbo-jet engines.

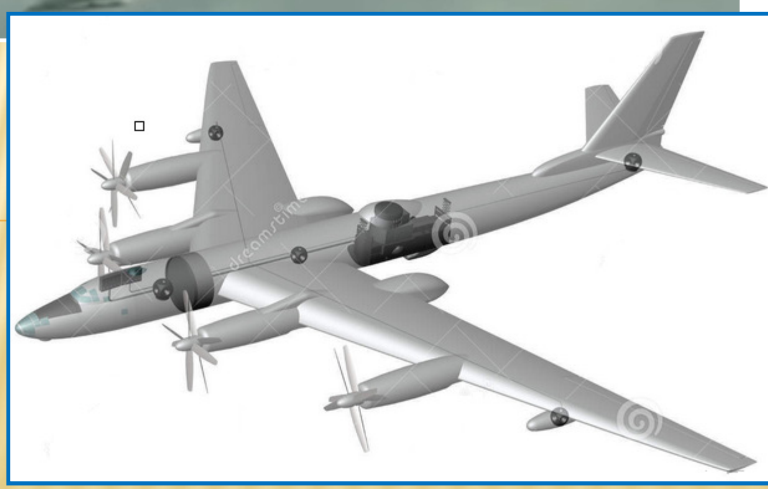
«Aviation week» 1958

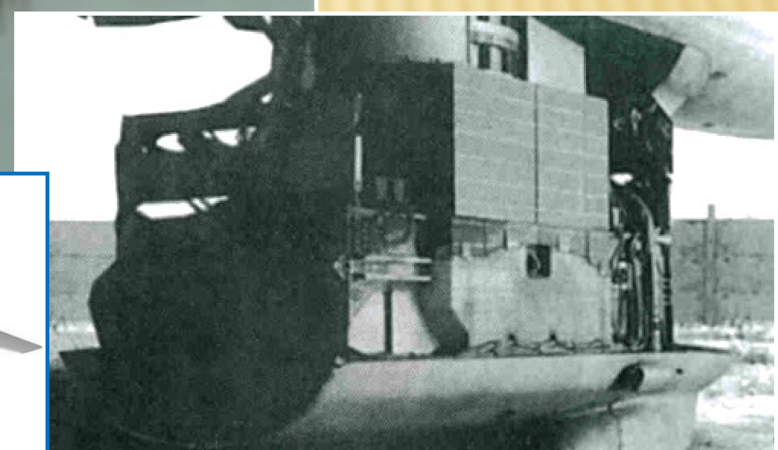
Tu-95 LAL (Летающая атомная Лаборатория) was a soviet bomber aircraft used as flying nuclear laboratory (Based on Tupolev Tu-95 design –«*The Bear»*)

It flown from 1961-1965 testing airborne operation of a reactor and shileding for components and crew.



- Most of flight tests made with the reactor shut down
- The reactor used the direct air-cycle configuration and very basic shielding system





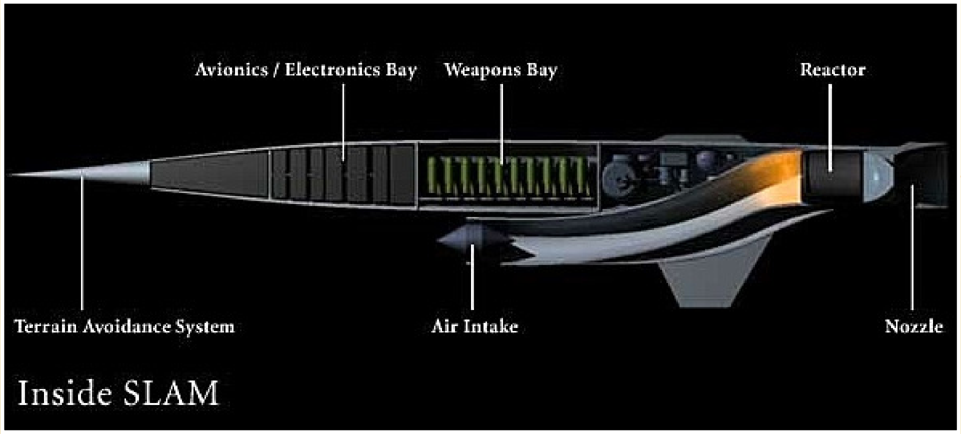
The reactor installed in the bomb-bay

OTHER PROJECTS

Supersonic Low Altitude Missile (SLAM): unmanned nuclear-powered ramjets capable to fly below the cover of enemy radar at supersonic speed and deliver thermonuclear warheads (very high energy consuming flight for traditional chemical engines)

- U.S. Air Force project conceived around 1955 and cancelled in 1964
- Nuclear engine in direct cycle configuration
- Low-altitude range: 182,000 km
- Cruise speed: Mach 3

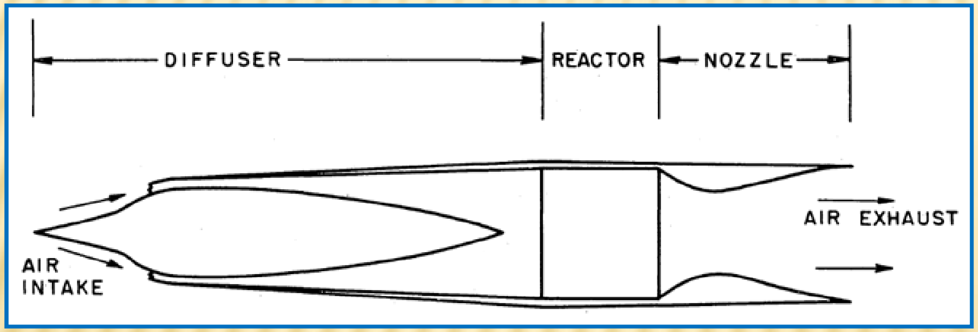
The SLAM design



The nuclear ramjet design

- In ramjet design both compressor and turbine are removed
- A static inlet with special geometry (diffuser) slows down the incoming air flow and increase its pressure (up to 3.8 MPa @ Mach 3)
- Ramjet requires a high-speed to impinge the air-flow

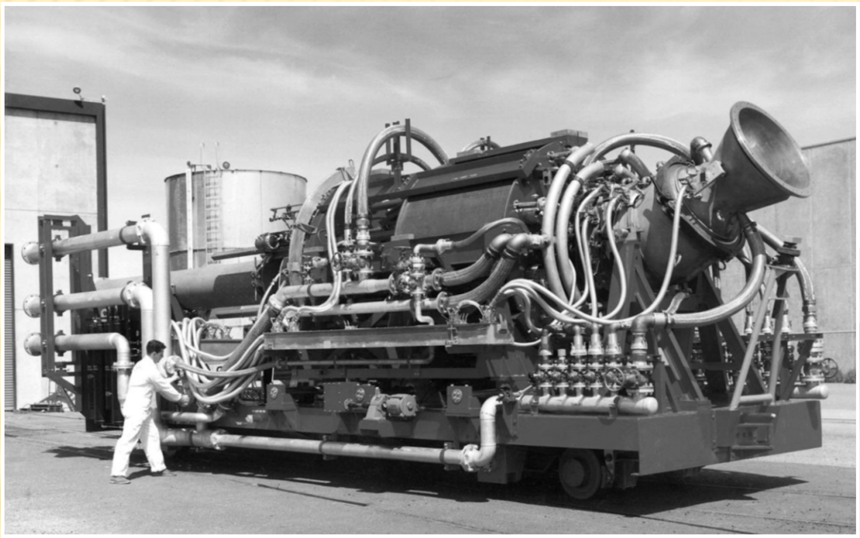
→ to be launched from the ground by a cluster of conventional rocket boosters



Conceptual arrangement of a nuclear ramjet

- Once it reached cruising the nuclear reactor would be made critical
- The reactor heat up the air and discharge it directly in the propulsive nozzle

- Nuclear engine developed under the project code-named **PLUTO**
- The project produced two working prototypes: **Tory-II A** (scaled-down variant) and the **Tory-II C** (full scale variant).



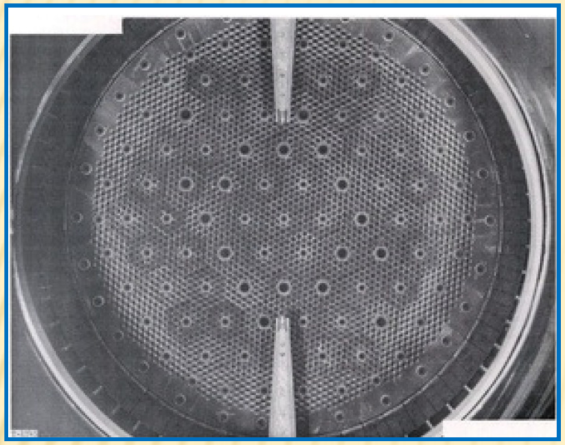
Tory-II A

Tory-II C

- Both successfully tested in the Nevada desert (1961-1964). Tory-II C run for almost 5 minutes at full power

Project cancelled in 1964 → system considered both highly problematic from engineering point of view (at that time) and provocative

Tory-II C nuclear reactor



Core of the Tory II-C test reactor

Thermodynamic performance

Flight Mach number:	3.0
Ambient temperature:	38 ℃
Altitude:	300 m

Reactor inlet-air temperature:	572 ℃
Reactor inlet-air pressure:	2.4 MPa
Maximum fuel wall temp.:	1371 ℃
Reactor flow rate:	845 kg/s
Net trust:	~ 15000 kg

Core design

Reactor type: homogenoeus

Configuration: 300.000 hexagonal fueled and unfueled tubes

Fuel : UO_2 (~ 52 kg) @ 92.3% in ^{235}U (in tube 0.1 m long)

Moderator: BeO + ZrO_2 for structural stability

Reflector:	BeO
Control rod material:	14 Hafnium rods
Core coolant:	Air
Over-all length:	1.6 m
Active length:	1.3 m
Nominal diameter:	1.2 m
Thermal output:	500 MW

Fuel cons. : ~ 500 gr / full-day power (1% total fuel mass)
→ several days of continous operation

END of STORY ???

LATEST NEWS…..

Northrop Grumman RQ-4 Global Hawk

February 2003

NewScientist

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Nuclear-powered drone aircraft on drawing board

TECHNOLOGY 19 February 2003

The US Air Force is examining the feasibility of a nuclear-powered version of an unmanned aircraft. The USAF hopes that such a vehicle will be able to "loiter" in the air for months without refuelling, striking at will when a target comes into its sights.

Feasibility studies

The US Air Force Research Laboratory (AFRL) has funded at least two feasibility studies on nuclear-powered versions of the Northrop-Grumman Global Hawk UAV (pictured). The latest study, revealed earlier in February at an aerospace technology conference in Albuquerque, New Mexico, concluded that a nuclear engine could extend the UAV's flight time from hours to months.

March 2018

THE | DIPLOMAT
Read The Diplomat, Know the Asia-Pacific

Russia Reveals ‘Unstoppable' Nuclear-Powered Cruise Missile

Putin announced a new high-yield intercontinental-range cruise missile purportedly capable of penetrating any missile defense system.

By Franz-Stefan Gady
March 02, 2018

Image Credit: YouTube Still Shot

Russian President Vladimir Putin announced during his annual State of the Nation address on March 1 that the Russian defense industry has begun developing an intercontinental-range nuclear-powered cruise missile capable of penetrating any interceptor-based missile defense system.

“We've started the development of new types of strategic weapons that do not use ballistic flight paths on the way to the target. This means that the missile defense systems are useless as a counter-means and just senseless,” Putin said in his speech.

“One of them is creation of a small-size highly powerful nuclear power plant that can be planted inside the hull of a cruise missile identical to our air-launched X-101 or the United States' Tomahawk, but at the same time is capable of guaranteeing a flight range that is dozens of times greater, which is practically unlimited,” he added.

Febraury 2019

RUSSIAN NEWS AGENCY

Tests of Burevestnik nuclear powered cruise missile successfully completed, says source

"A major stage of trials of the cruise missile of the Burevestnik complex, the tests of the nuclear power unit, were successfully completed at one of facilities in January," he said

MOSCOW, February 16. /TASS/. The tests of the compact nuclear power unit for cruise missile Burevestnik have been successfully competed in Russia, a source in the missile producing industry told TASS.

"A major stage of trials of the cruise missile of the Burevestnik complex, the tests of the nuclear power unit, were successfully completed at one of facilities in January," he said.

The trials "sustained stated specifications of the reactor ensuring the missile’s unlimited range," the source added.

The 9M730 Burevestnik missile under test

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NEWS · 30 AUGUST 2019

How nuclear scientists are decoding Russia's mystery explosion

Isotopes that caused a radiation spike earlier this month probably came from an exploding nuclear-reactor core — but device's application is still unknown.

A day after the blast, Russia's nuclear agency, Rosatom, said that an accident happened during "tests on a liquid propulsion system involving isotopes" and later added that the incident happened on an offshore platform.

August 2019

The New York Times

Russia Confirms Radioactive Materials Were Involved in Deadly Blast

6/9/2019

le Scienze

edizione italiana di Scientific American

I fisici nucleari indagano sulla misteriosa esplosione russa

- The explosion caused a brief spike in γ-radiation (16 times normal level) in the city of Severodvinsk (30 km east the Navy base of Nenoska)

- On 26 August, the Metereological Russia Agency «Roshydromet» detected the following isotopes in rain and air: ^{91}Sr, ^{139}Ba, ^{140}Ba, ^{140}La

- Five scientists killed due to the explosion

- Of the eight stations across Russia that monitor radionuclides five of these had outages in the days after the blast (why ?)

The Russian Navy base of Nenoksa

Thanks for your attention!

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