Nuclear-powered jet engines: the bad idea that has not gone away

By **Jim Thomson**

SUMMARY

- From 1946 until 1964, the United States pursued nuclear-powered aircraft in a series of overlapping projects, for both manned and unmanned aircraft, before abandoning the idea.
- The Soviet Union also pursued nuclear-powered aircraft from 1955 until the early 1960s.
- The notion of nuclear-powered flight then disappeared until, in 2018, President Vladimir Putin revived the idea by announcing that a Russian nuclear-powered cruise missile was in development.

1. INTRODUCTION

The history of nuclear-powered jet engines has been erratic. The downsides were many: weight, radiation and shielding requirements, power density, insufficient fuel temperature, airborne contamination, and activation products, and crash safety. From a 21st century western perspective, these difficulties seem to outweigh any potential advantages of more prolonged flight duration. However, in the Dr Strangelove world of the early Cold War, the US Air Force (USAF) was enamoured with the idea of fleets of nuclear-powered bombers that could remain airborne for weeks at a time. Undoubtedly inter-service rivalry was also a factor – nuclear-powered bombers championed by USAF Strategic Air Command under General Curtis LeMay were, in effect, in competition with land-based intercontinental ballistic missiles and with Admiral Hyman Rickover's pressurised water reactors for US Navy submarines. All three – nuclear-powered bombers, land-based intercontinental ballistic missiles, and ballistic missile submarines - potentially offered the means to counter the perceived Soviet threat in the 1950s. Another alternative – unmanned long-duration nuclear-powered cruise missiles - was also explored by the US. All work on the nuclear-powered flight was abandoned in the USA by 1964, and in the USSR at about the same time. The idea remained moribund until revived by Russia in 2018.

2. THE UNITED STATES' EFFORT ON NUCLEAR-POWERED AIRCRAFT

The USA had three main overlapping programmes investigating nuclear-powered jet engines:

The Nuclear Energy for the Propulsion of Aircraft (NEPA) project carried out feasibility studies between 1946 and 1951 via a contract from the US Army Air Forces (USAAF, which became the USAF in 1947) to the Fairchild Engine and Airplane Corporation. The NEPA project was carried out at Oak Ridge National Laboratory (ORNL), Tennessee. The work began with a surge of optimism – a review published in September 1948 concluded that "although success could not be guaranteed, there was a strong probability that some version of nuclear-powered flight could be achieved if adequate resources and competent manpower were put into the development". The NEPA project was wound up in 1951 with the conclusion that "nuclear propulsion of aircraft was technically feasible".

This positive review of feasibility led to the USAF and the Atomic Energy Commission (AEC) jointly initiating the Aircraft Nuclear Propulsion (ANP) program. This ran between 1951 and 1961 and was intended initially to yield operational aircraft powered by nuclear-heated turbojets. As the difficulties of this became apparent, ANP was reduced in scope to producing a viable nuclear turbojet before cancellation in 1961.

Finally, Project Pluto ran between 1957 and 1964. It was intended to produce a nuclear-heated ramjet-powered cruise missile called SLAM (Supersonic Low-Altitude Missile).

2.1. Design and performance of nuclear jet engines vs. conventional jet engines

In the late 1940s and 1950s, it perhaps seemed reasonable that two new technologies – turbojets and nuclear reactors – could be merged: a nuclear-powered turbojet would use nuclear heat in place of the chemical heat of fuel combustion. Otherwise, the basic structure of a turbojet (i.e., air inlet-compressor-combustion chamber-turbine-exhaust) would be retained.

What is surprising, with 21st century hindsight, is that this absurd idea passed even basic scrutiny of its plausibility. A few simple (perhaps simplistic) and approximate sums illustrate the problem:

- The specific fuel consumption of a typical 1960s turbojet (GE J79 without afterburn): 24 g/kN.s.
- Typical jet fuel specific heat of combustion: 43 kJ/g.
- Hence 1 kN thrust requires 24 g/s jet fuel flow, or (24*43) = 1032kW of heat input approximately.

The USAF's Convair B-58 Hustler supersonic bomber, first flown in 1956, used 4x46kN GE J79 turbojets - say 200kN combined engine thrust. Thus, 200 kN thrust (=~45000 lbf) for a nuclear turbojet-powered bomber would require at least (200*1032kw) = ~206 MW of nuclear heat if the heat could be delivered at a high enough temperature (930°C for a J79). Lower temperature would impair performance significantly.

Turbine entry temperature is an important performance indicator of jet engines. In a typical jet engine of c.1960, turbine entry temperatures of >900°C were achieved (Table 1). Modern jet engines can achieve ~1500°C because of special arrangements for cooling the combustion chamber structure. Nuclear heat at such high temperatures could not readily be delivered using conventional metal-clad nuclear fuel, because of fuel clad temperature limits, so the ability to convert nuclear heat into turbojet thrust was limited.

As well as thermal performance, the weight of the reactor and its shielding were also important to the viability of nuclear aircraft propulsion, although this would be offset to some extent by the

Engine	Whittle W.1 (centrifugal fan single shaft turbojet)	GE J47 (single shaft turbojet, data are without afterburn)	GE J79 (single shaft turbojet, data are without afterburn)	GE J87 *(proposed nuclear turbojet to meet 1955 specification WS-125-A)*	Rolls-Royce Olympus 593 (Concorde) (two shaft turbojet, data are without afterburn)	Rolls-Royce Trent 1000 (three shaft high bypass turbofan)
Year of first flight	1941	1948	1955	*Never built, cancelled 1959*	1969	2007
Thrust	850 lbf /~4 kN	~5000 lbf /~22 kN	11900 lbf /~53 kN	13685 lbf /61 kN (design intent)	31300 lbf /139 kN	~70000 lbf /~311 kN
Pressure ratio	3.8:1	5.35:1	13.5:1	20:1	15.5:1	50:1
Turbine inlet temperature	780°C	870°C	930°C	980°C	1150°C	~1500°C
Thrust-to-weight ratio	1.474	2.34	4.6	**	5.4	6.0
Specific fuel consumption (g/kN. s)	38.5	28.7	24	Not applicable	33.8 (cruise)	13.5

*Data are compiled from multiple sources.
** No straightforward comparison of thrust-to-weight between the nuclear-powered J87 and conventional jet engines is possible because of the weight of jet fuel in a conventional jet aircraft. However, the weight of the J87 was estimated as 115740 lbs (52.5 tonnes) including shielding and turbomachinery (ref.: APEX-907:XMA-1, Table 2.10, downloaded April 2021 from http://leehite.org/anp/documents.htm). To power a B-52 class bomber (loaded take-off weight >200 tonnes, empty weight 83 tonnes, powered by 8x76 kN Pratt & Whitney TF33 turbofans), many J87s would be needed – and their weight would mean the sums do not add up.

TABLE 1: Historical development of jet engine performance*

absence of jet fuel storage. The pressure ratio is also significant for performance. Finally, the size and shape of the reactor had to be suitable to fit in a streamlined airframe.

The challenge facing nuclear engineers was to try to produce a nuclear reactor that could transfer hundreds of megawatts of heat into a small volume at as high a temperature as possible. The nuclear reactor would be of similar heat output to a small nuclear power station – but much hotter, and airborne! Ideas proposed at first were molten salt reactors, liquid metal cooled reactors, and even supercritical steam reactors (imagine the flying pressure vessel!); in each of these proposals, the reactor coolant heated the compressed air in the jet engine. Later designs (the HTRE experiments) used a direct-cycle approach where the reactor was cooled directly by the compressed air in the turbojet.

Table 1 presents a comparison of the principal performance parameters of various jet engines since the 1940s and includes the specification for the unbuilt GE J87, which would have been a development of HTRE 3 (see text). The nominal GE J87 turbine inlet temperature was 40K higher than HTRE 3 achieved.

However, design predictions of the weight of the nuclear engines, including reactor and shielding (see footnote on Table 1), meant that a large nuclear-powered bomber was, literally, not going to fly.

The Pluto/SLAM project outlived the end of the nuclear turbojet. Pluto explored the use of a high-temperature ceramic-core reactor as the heat source in a supersonic ramjet, which would have no rotating turbine or compressor. Two prototypes, Tory-IIA and Tory-IIC, were operated in 1961 and 1964, but the proposed application (for an unmanned, and therefore unshielded, intercontinental cruise missile) became redundant in the era of ICBMs and Polaris submarines. Tory-IIC may have maintained a fuel surface temperature of 1300°C (see below).

2.2. The Aircraft Reactor Experiment (ARE) 1954, and the Aircraft Shield Test Reactor (ASTR) (1955-57)

Between 1951 and 1953, work at ORNL began on an Aircraft Reactor Experiment (ARE), and the USAF awarded (prematurely) a contract to Convair for a flying prototype aircraft. In addition, USAF/AEC awarded a contract to General Electric (GE) for a propulsion system (which GE expected to deliver as soon as May 1956), the USAF awarded a contract to Lockheed for the design of a series of airframes, and the USAF also awarded a contract to Pratt & Whitney (P&W) for development of a supercritical water reactor for airborne application - although the latter was terminated in June 1954 and P&W were redirected initially to support molten salt reactor studies, and later to solid-fuel, liquid metal-cooled reactor studies. (Frankly, the idea of an airborne pressurised water-cooled reactor is absurd.)

For the Aircraft Reactor Experiment (ARE) (Figure 1), the AEC National Reactor Testing Station (now Idaho National Laboratory) was selected as a suitable site. ARE was a molten salt reactor where the fuel consisted of 53% NaF, 41% ZrF_4, and 6% UF_4,

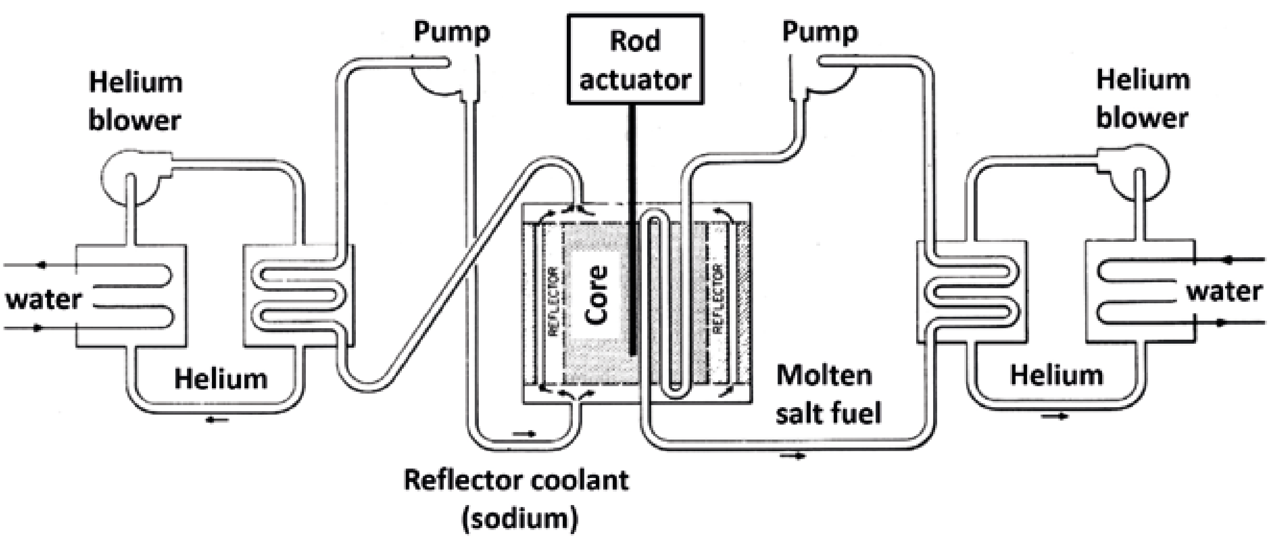

FIGURE 1: A schematic diagram of the land-based Aircraft Reactor Experiment (ARE), which was operated during November 1954 at Idaho National Laboratory [2]. Separate loops for reactor cooling (molten salt to helium) and BeO reflector cooling (sodium to helium) are shown.

FIGURE 2: The Convair NB-36H Crusader with the Aircraft Shield Test Reactor – the only US aircraft to have flown while carrying an operational nuclear reactor. The radiation symbol can be seen on the vertical stabiliser. A Boeing B-50 Superfortress chase aircraft is also shown, which indicates the size of the NB-36H. (USAF)

with highly enriched uranium (>90% U-235). Molten salt was considered suitable for heating a nuclear turbojet because of the high temperatures needed. ARE was operated successfully over 9 days in November 1954 at a power of up to 2.5 MW, using 14.9 kg of U-235. The reactor was moderated with beryllium oxide, and there was a separate liquid sodium coolant loop for the BeO reflector. In tests, the molten salt fuel achieved temperatures of 980oC. The reactor was stable with a strong negative temperature coefficient. Increased chromium in the molten salt during the few days' operation indicated that corrosion of the Inconel tubing was occurring, although the significance of this is unclear.

Although ARE was the first molten salt reactor, and the first reactor to demonstrate temperatures in the range needed for a turbojet application, its power was much too low for this purpose. A larger successor prototype - the 60 MWth Aircraft Reactor Test (ART) was in development from 1954 onwards, although this was still much too small for use in bombers. In late 1956 project reviews indicated that hitherto declared in-service dates for nuclear bombers had been wildly optimistic, and the program was re-focussed.

Separately from the ARE development, Convair and GE proceeded with the Aircraft Shield Test Reactor (ASTR), a low-power (1 to 3 MWth) water- and air-cooled reactor fitted onboard a modified giant B-36 Peacemaker bomber called the NB-36H Crusader (Figure 2). The objective of the NB-36H was to demonstrate that the flight crew could be adequately shielded from an airborne reactor – the reactor thermal power was not used for any purpose. The aircraft had a modified nose section, containing all the aircrew, that included 12 tonnes of lead and rubber shielding. This aircraft made 47 test flights between September 1955 and March 1957 over Texas and New Mexico – and these remain the only occasions on which an operating reactor has flown on an American aircraft.

2.3. Politics and reality

On at least two occasions, the ANP programme to produce a nuclear turbojet was reduced in priority before being increased again. There were also frequent changes of emphasis which appear to have been caused by the difficulties in realising the objective. The technical problems were fundamental, but it took a while for decision-makers to accept that.

In April 1955, the USAF awarded preliminary design study contracts to Convair, Lockheed, and Boeing for a design competition against a requirement WS-125-A to provide a "nuclear-powered, piloted bombardment weapon system capable of delivering nuclear munitions against any target in the world." This was clearly premature since the nuclear turbojet was nowhere near ready, with widely varying design concepts under consideration – perhaps this was an indication of the lack of understanding and communication between engineers and generals. These contracts enabled large sums of money to be spent on development facilities (such as a large shielding test facility built in Georgia by Lockheed that was hardly ever used).

Further evidence of the disconnect between engineers and decision-makers was provided in mid-1956 when the Air Force Chief of Staff told the Joint Committee on Atomic Energy that he believed there was a strong requirement for nuclear-powered aircraft. First flight by 1960 was suggested, with a requirement for 120 nuclear power plants for 30 aircraft by 1964 - at a time when no-one seemed sure about what an operational nuclear turbojet (if such a thing could be built at all) might look like.

By October 1956, though, more cautionary noises were being made: An Air Force advisory panel noted that “While the present state of the reactor art is encouraging, it does not conclusively prove that a useful vehicle can be built.” It was recommended that the scope of the nuclear-powered supersonic aircraft system be changed to that of a research program, and this was accepted by the Secretary of Defense. Even if nuclear-powered bombers could be made to work, they would leave a trail of activation products (Ar-41 and N-16) behind them – and worse if the nuclear fuel leaked. Requirement WS-125-A was cancelled in December 1956.

In October 1957, following the launch of Sputnik, there were calls to increase effort again on nuclear bombers. Further calls to increase effort occurred in December 1958 when the influential magazine Aviation Week published an article claiming (falsely) that the Soviet Union was already testing a nuclear-powered bomber. This claim was later shown to have been based on reports of the conventionally powered Myasishchev M-50 (NATO code name BOUNDER) supersonic jet bomber - a design that was itself unsuccessful. (Only one was built.) One might speculate, of course, about whether this story might have originated from someone with a vested interest in keeping the ANP project alive. In the late 1950s, US politicians and the public alike were nervous about supposed ‘missile gaps’ and ‘bomber gaps’ – unfounded claims that the Soviet Union was leaving the USA behind in offensive technologies. Aviation Week continued to publish occasional articles advocating further effort on nuclear-powered bombers, for example, an editorial in March 1959 entitled “The case for nuclear-powered aircraft”.

The ANP programme survived until the end of the Eisenhower administration, but the newly elected President Kennedy promptly killed it off on 26 Mar 1961, announcing “15 years and about $1 billion have been devoted to the attempted development of a nuclear-powered aircraft, but the possibility of achieving a militarily useful aircraft in the foreseeable future is still very remote”.

Project Pluto lasted a further 3 years before it too was cancelled. By 1964, the successful development of intercontinental ballistic missiles and nuclear-powered submarines had made nuclear-powered aircraft and missiles superfluous.

2.4. The HTRE program to develop a nuclear turbojet 1955-1961

After the cancellation of the WS-125-A program in December 1956, the ANP programme continued without any clear flight objectives. Engine development under General Electric continued

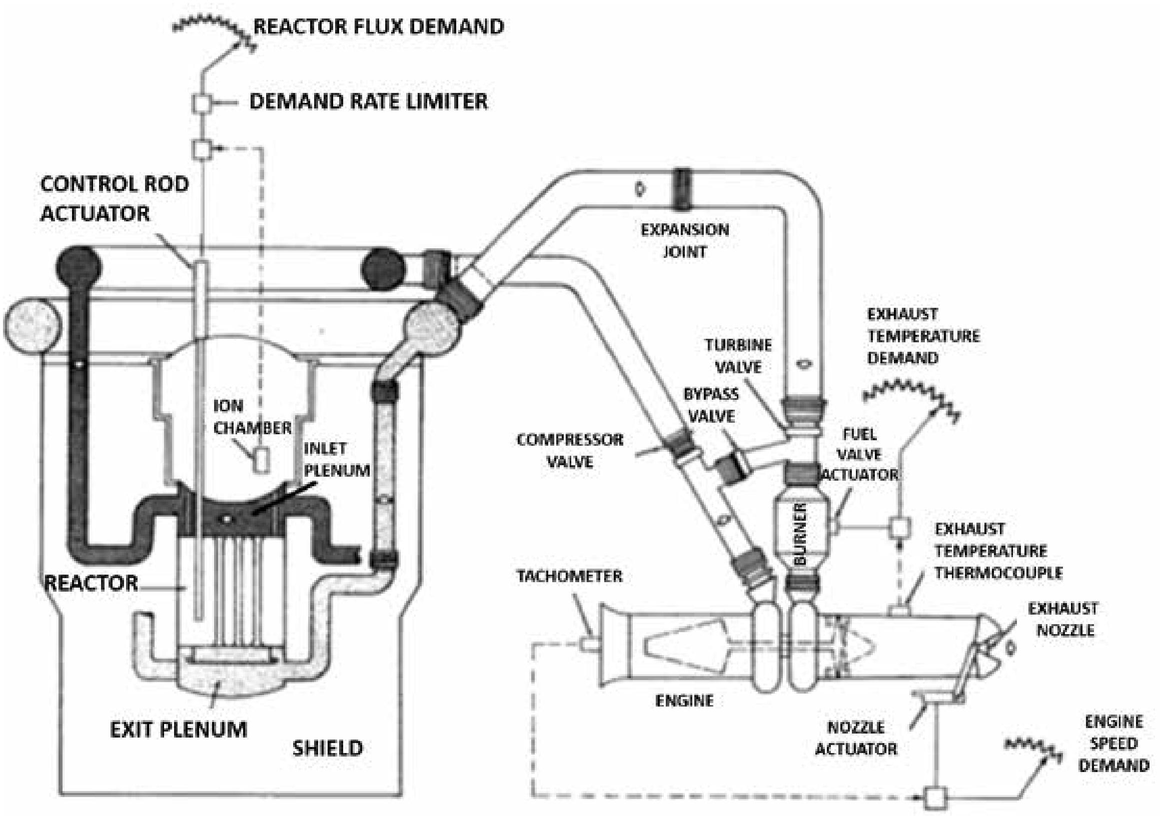

FIGURE 3: Schematic diagram of HTRE-1/HTRE-2. The turbojet was started up using jet fuel and only then switched over to nuclear heat [4]

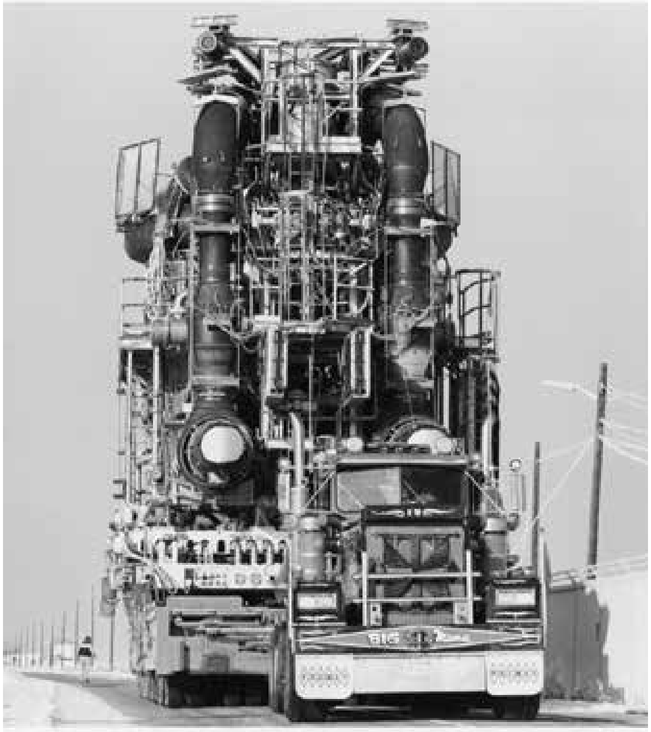

FIGURE 4: HTRE-1/HTRE-2 was enormous yet produced little thrust. (Idaho National Laboratory)

with the Heat Transfer Reactor Experiments HTRE-1, -2 and -3 at the National Reactor Test Station in Idaho.

HTRE-1 – with a water-moderated, air-cooled reactor with Ni-Cr-UO_2 fuel - went critical in November 1955, and in January 1956 it supplied nuclear heat to a modified GE J47 turbojet[1]. This was the first time that a turbojet had been operated exclusively using nuclear heat.

One description of HTRE-1 (Figure 3) says [4]: "HTRE-1…… was mounted on a huge mobile railroad car assembly. It was a water-moderated uranium reactor with a beryllium reflector and shielding that included large quantities of mercury. (The jet engine) would be started using hot gas produced by chemical fuel combustors. Once the jets were running at speed, the reactor would be brought up to power and airflow would be established through the core. Its heat would then be gradually diverted to the jet turbines as the gas combustor flow was phased out. (The jet) would be run on nuclear heated-air for hours at a time to simulate the operation of a long-duration nuclear aircraft powerplant. Post-shutdown, the reactor's railcar would be returned to a maintenance bay for disassembly and analysis. HTRE-1 reached power levels as high a 20.2 MW. It was later modified to become HTRE-2 and was used for testing special core configurations and materials, reaching power levels of around 14 MW." HTRE-2 tests were conducted during July and August 1957.

HTRE-1/HTRE-2 was a massive machine which (Figure 4) was far too low-powered to be flight-capable – it could barely generate enough power to keep the jet engine running. The turbine entry temperature was <730°C [3]. Data on achieved thrust levels were not released but must have been low.

HTRE-3 was closer to a flight-capable design (Figures 5 and 6). The reactor had a horizontal layout, with a relatively lightweight aluminium structure. The HTRE-3 power plant assembly consisted of a zirconium hydride-moderated reactor, 80% nickel-20% chromium-clad fuel elements containing 93%-enriched $U^{235}O_2$ embedded in a matrix of 80Ni-20Cr, beryllium reflector, and primary and removable auxiliary shielding. The core contained 178 kg of U-235. There were three control rods made of europium oxide. The entire machine was mounted on a railcar with a shielded locomotive to move it to and from the test area.

HTRE-3 operated from October 1958 to January 1961. It operated in a power range of up to 35 MW. The jet engines could be brought to power on nuclear heat alone (unlike HTRE-1 and HTRE-2). Hence HTRE-3 was the first true nuclear-powered turbojet.

On 18 November 1958, a reactivity accident occurred which resulted in melting of a significant part of the core [5]. The accident was caused by a control system fault, apparently due to multiple unrevealed defects in installation. It appears that commissioning tests had been inadequate to reveal the C&I defects, either because the tests were poorly conceived or else poorly carried out. The accident report says:

"The cause of the power excursion was the addition of reactivity brought about by the control system withdrawing dynamic and shim rods in normal sequence. This action occurred in response to a false demand caused by a less-than-actual indication of reactor power. The false indication of the linear ion chamber circuit is attributed to its installed condition as opposed to any inherent fault in design. Two safety actions did not occur, either of which, in theory, could have stopped the excursion. The first was a power-level limit, which existed on two linear ion chamber channels, neither of which could indicate the correct level because of the condition of their installation. Although the period safeties[2] operated by the log flux channels were retained in operation because of the low level, the period indication was incorrect. Saturation of the period circuits prevented any period signal that could initiate the safety actions associated with the period indication. Examination of the reactor indicates that all the fuel cartridges experienced melting in the middle stages. The amount of heat required to produce such melting is consistent with the total energy release of 770 megawatt-seconds."

FIGURE 5: HTRE-3 powered the first true nuclear-powered turbojets. It was a ground-based prototype for possible use in an aircraft. It produced significant jet thrust and was able to start itself using nuclear heat. It suffered a fuel melt in its first few weeks of operation in November 1958; the core was replaced, and it was operated until early 1961. (Idaho National Laboratory)

1 When used in nuclear aviation research, GE J47s were called X39s.

2 The reactor period (T) is the time for the reactor power to increase by a factor e. A period safety trip function will initiate reactor shutdown if T is less than a defined value.

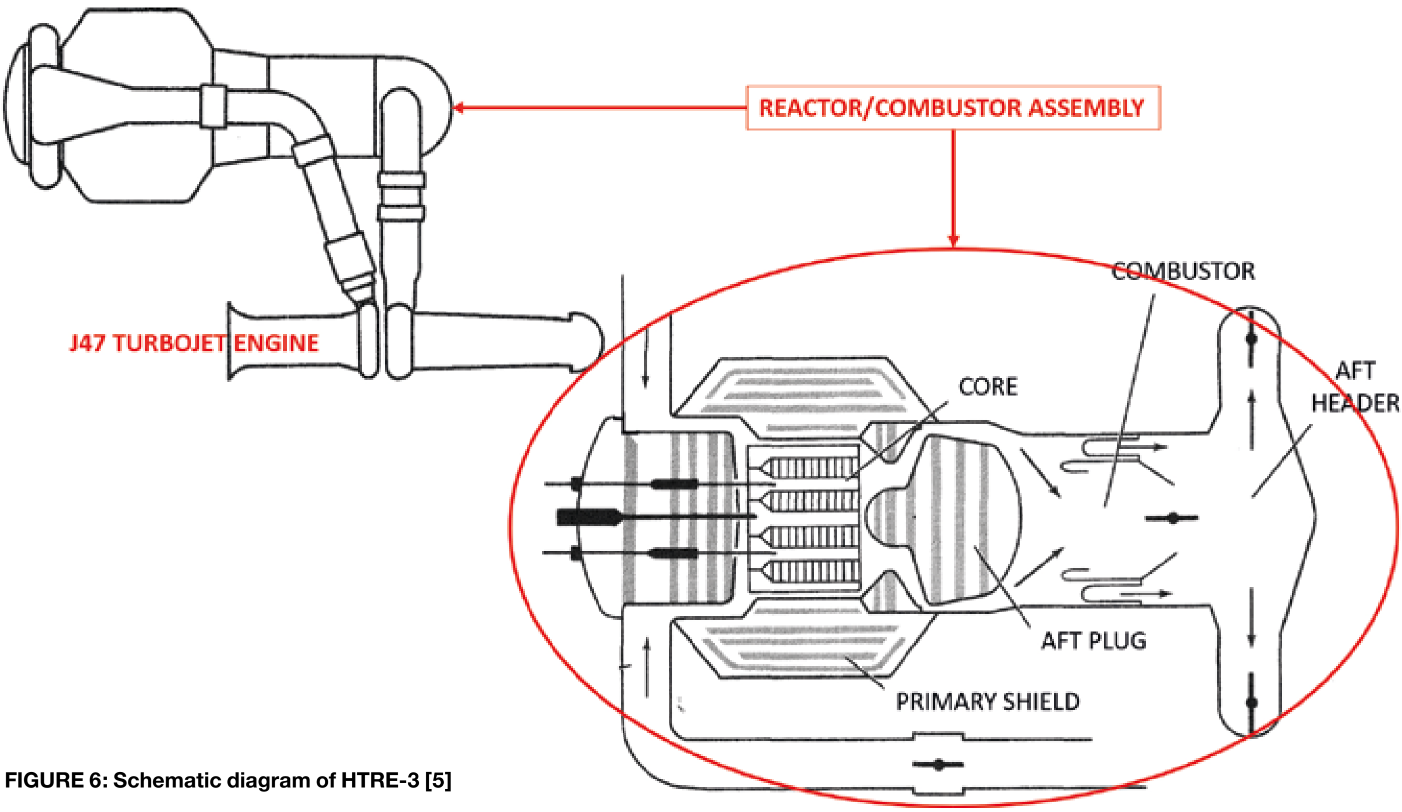

FIGURE 6: Schematic diagram of HTRE-3 [5]

Instantaneous maximum power was not established precisely but was certainly several hundred megawatts (compared to the design power of 35 MW). The accident released ~17 GBq of I-131, ~25 GBq of Sr-91, and other isotopes.

After the accident, the damaged core was removed, the machine was decontaminated, and the core was replaced. Testing resumed with improved control arrangements. HTRE-3 achieved turbine entry temperatures of c.940°C[3] at up to its full 35 MW design power during tests over a further two-year period, until President Kennedy closed the ANP project in March 1961. A 1965 RAND Corporation review [15] observed:

"The final tests on HTRE-3 resulted in an air temperature considerably lower than that desired for military application."

In other words, the nuclear turbojet could not generate enough thrust to be worthwhile. However, another source says that "Despite the fact that HTRE-3 did not produce the power that would have been needed for flight, that was mainly because it was not an optimized design; it was designed simply as a research reactor, to prove the concepts needed for a flight article. At the end of the HTRE run the probability of flying a reactor seemed high. The test runs showed that a reactor using the same materials as HTRE-3, and which could power a gas-turbine powerplant, could have been built at that time."

HTRE tests ended with President Kennedy's termination of the ANP program in 1961.

3 So far as I can tell, data on thrust levels achieved by HTRE-3 have never been published but values of the order of 35 kN (~8000 lbf) may be inferred. This was nowhere near enough to power a c.200 tonne bomber as had been envisaged, and multiple HTRE 3 engines would have been too bulky and heavy.

2.5. SLAM and Project Pluto 1957-1964: the nuclear ramjet

Despite waning interest in nuclear turbojets and cancellation of the ANP program in 1961, another project called Pluto had started in 1957. Pluto's aim was to develop a nuclear ramjet to power an unmanned cruise missile called SLAM (Supersonic Low-Altitude Missile). Although SLAM itself never flew, prototype ramjets called 'Tory-IIA' and 'Tory-IIC' were designed by the Lawrence Livermore Radiation Laboratory of California and operated at the Idaho site under the direction of T.C. Merkel [6, 7]. If the project had been completed successfully, SLAM might have been capable of remaining airborne for many days and could have carried multiple warheads. Development was also begun into autonomous navigation using a terrain-comparison radar guidance system. (This technology was eventually used in conventionally powered cruise missiles brought into service in the 1980s.)

The nuclear ramjet (Figure 7) does not require rotating parts - compression is achieved by means of high-speed airflow into a diffuser. This means that SLAM would have required rocket boosters to get airborne and to achieve supersonic speeds before

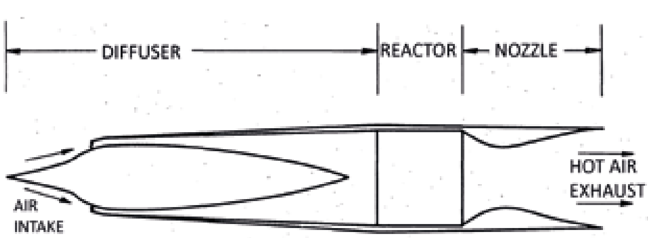

FIGURE 7: Conceptual layout of a nuclear-powered ramjet.

the nuclear-powered ramjet could become effective. The reactor would have been situated in the middle of the ramjet casing and would have had to be able to maintain fuel surface temperatures above 1300°C with a thermal power of 600 MW.

Thus, the success of Project Pluto depended upon a whole series of technological advances in metallurgy and materials science. Ceramic fuel was required – a mixture of beryllium oxide, highly-enriched UO_2, and zirconium dioxide - and a contract was placed for 500000 hollow, pencil-sized fuel elements, each 10 cm long with an inside diameter of 5.8mm. The cylindrical core would have contained 27000 airflow channels.

The two prototypes, Tory-IIA and Tory-IIC, were built and tested successfully at the Idaho site. Static testing of the ramjets required special effort since it was necessary to create and maintain supersonic airflow. To achieve this, 40 kilometres of oil-well casing pipework were obtained to store pressurised air, which was supplied by giant compressors borrowed from the US Navy. Testing required a flow rate of up to one tonne of air per second, to be maintained for several minutes. The reduced-scale Tory-IIA ran successfully for a few seconds in May 1961. This was superseded by Tory-IIC (Figure 8), a full-scale prototype that operated for five minutes in May 1964. Tory-IIC produced 513 MW of heat, 156 kN (35000 lbf) of thrust, and deafening levels of noise. Tory-IIC was therefore the world's first viable nuclear jet engine for aircraft propulsion – although the difference between a few minutes' operation during an experiment and several days' operation deployed in a SLAM cruise missile might have been significant.

FIGURE 8: The Tory-IIC nuclear ramjet which was successfully tested in Idaho in May 1964.

Despite the successful test, SLAM would very probably have been in contravention of international treaties, and for various reasons, it would have been untestable over the United States – these included noise, radiation, contamination, and accident risk. SLAM would have been a supersonic, unshielded, uncontained, unmanned, 600 MW air-cooled flying reactor carrying nuclear warheads. What could go wrong?[4]

By 1964 the US Air Force was deploying ICBMs and the US Navy was deploying Polaris submarines. By comparison, SLAM looked distinctly less attractive as a strategic weapon (Figure 9).

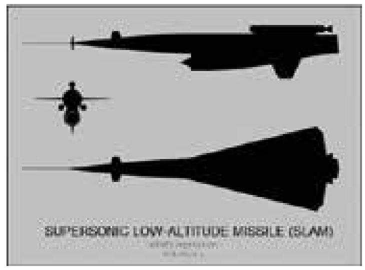

FIGURE 9: An artist's impression of SLAM, the Supersonic Low-Altitude Missile powered by a nuclear ramjet. It was never built.

On 1 July 1964, Pluto and SLAM were cancelled. Its cost had been $260 million [8].

3. SOVIET/RUSSIAN EFFORTS

Meanwhile, in 1955 in the Soviet Union, the Council of Ministers decreed the development of a nuclear-powered bomber. Information about the Soviet efforts are less clear than the American developments, but they seem to have followed similar paths. Some information can be gleaned from Russian websites [9-11].

A Tupolev Tu-95 BEAR bomber was adapted to carry a 100kW reactor (named VVRL-100) in its bomb bay as a shielding test – thus becoming the Tu-95LAL, where the Russian acronym LAL stood for 'Flying Atomic Laboratory' (Figure10). This aircraft completed 34 flights between May and August 1961 from a test site near Semipalatinsk in northeast Kazakhstan. The main task was to examine the effectiveness of the radiation shielding to

FIGURE 10: The Tupolev Tu-95LAL reactor shielding test carried the 100kW VVRL-100 reactor in its bomb bay during 34 flights in 1961.

4 There would have been many other technical obstacles before SLAM could ever have been deployed. For example: no aircraft has ever flown at low altitude at Mach 4 because of kinetic heating constraints; the very novel navigation system would have needed to be radiation hardened; and the warheads would have had to be protected from the reactor neutron flux.

FIGURE 11: A technician working on Burevestnik/SKYFALL nuclear-powered cruise missiles in a large workshop. The missiles are partly covered but are reported to be ~9m long. This is taken from https://www.youtube.com/watch?v=okS76WHh6FI&feature=emb_title

protect the crew in the front pressurised cabin. Shielding was deemed to have been adequate.

Plans were developed for nuclear-powered bombers, but common sense prevailed and research into nuclear-powered aircraft was cancelled in the first half of the 1960s [12] – possibly even as early as 1961 [11]. With the demise of SLAM in 1964 and the end of Soviet work at about the same time, the era of nuclear-powered flight seemed to be over.

Then, to general surprise, Vladimir Putin announced on 1 March 2018, that Russia was developing a nuclear-powered cruise missile. This has since been named Burevestnik ('Petrel') and has been given the NATO designation SSC-X-9 SKYFALL (Figure 11). It was reported to be 9m long.

On 9 August 2019, Rosatom confirmed a release of radioactivity at the State Central Navy Testing Range near Severodvinsk in northern Russia and stated it was linked to an accident involving the test of an "isotope power source for a liquid-fuelled rocket engine". Five weapons scientists were killed in the accident. It has been suggested that this accident was linked to the development of Burevestnik/SKYFALL, but this remains uncertain [13].

All the difficulties listed above for SLAM will also apply to Burevestnik/SKYFALL if it ever reaches operational status.

4. CONCLUSIONS

Total US expenditure on both, ANP and Pluto, was about $1.3 billion (uncorrected for inflation) [14]. The initial objectives of the two programmes (nuclear-powered crewed bombers and pilotless cruise missiles, respectively) were not met, and the expenditure provided almost no useful return.

A critique of the programs was provided by the RAND Corporation in 1965 [15]. Although written in a difficult bureaucratic style, the report nonetheless contained some hard-hitting points:

"Novel and advanced propulsion systems …(are) characterised by high estimated development costs, deficiency in technological data, and usually an absence of an application requirement."

"When chemically fuelled engines can perform the same mission, they usually prove superior to the nuclear system in terms of cost-effectiveness…."

Regarding the practicality of nuclear-powered submarines vs. nuclear-powered aircraft, it has been noted pithily that it is "much easier to float shielding than to fly it" [16].

In the 21st century, it is unclear what President Vladimir Putin hopes to achieve by trying to develop nuclear jet engines for Burevestnik/SKYFALL, except perhaps an appeal to Russian nationalism. It would require dramatic and unlikely technological advances to overcome the disadvantages of nuclear jet engines.

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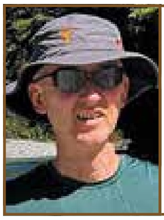

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