Nuclear Engine Air Power

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ISBN: 9781925062403 (print version)
9781925062410 (online PDF version)

A catalogue record for this book is available from the National Library of Australia.

Published and distributed by:
Air Power Development Centre
F3-G, Department of Defence
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CANBERRA BC 2610
AUSTRALIA

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Foreword

Beyond the Planned Air Force (BPAF) introduced a series of topics that extend Air Force's perspective beyond the objective force envisioned in both the Defence White Paper 2016 and the Defence Integrated Investment Plan. Expanding upon this initial publication, the BPAF series of papers seeks to identify and explore in greater depth how technological, societal, and environmental disruptors and drivers may shape Air Force's ways and means of providing air power for Australia.

This working paper has been prepared by the Air Power Development Centre to explore possibilities for nuclear-engine air power. A nuclear incident in Russia, in August 2019, put the spotlight on a possible nuclear-propelled missile that was first publicly revealed by Russia's President Putin during his 2018 State of the Nation address to the Russian Federal Assembly in the Kremlin.

This publication will inform air power practitioners about the general characteristics, history, prospects, and risks of nuclear-engines and aid their understanding of the potentially disruption effects to Australian air and space power. This publication does not suggest that Australia should consider changing its attitude or position on nuclear weapons. The current national policy position is that, "Australia does not possess any nuclear weapons and is not seeking to become a nuclear weapons state. Australia's core obligations as a non-nuclear weapon state are set out in the Nuclear Non-Proliferation Treaty. This includes a solemn undertaking not to acquire nuclear weapons."[1]

The fundamental roles defined in air power doctrine will continue to be relevant into the near future, beyond that of the planned Air Force. Technology is beginning to realise new capabilities based on nuclear propulsion that may be a game-changer to disrupt both technological and political strategic-thinking, potentially necessitating a need to enhance the delivery and effectiveness of air power through new concepts in multi-domain operations.

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1 Australian Government (2019). Australia and Nuclear Weapons. Nuclear Issues. Department of Foreign Affairs and Trade. Online at: https://dfat.gov.au/international-relations/security/non-proliferation-disarmament-arms-control/nuclear-issues/Pages/australia-and-nuclear-weapons.aspx. Accessed 27 August 2019.

I recommend that readers also consider reading the APDC companion publications, "Hypersonic Air Power" and "Pseudosatellites: Disrupting Air Power Impermanence," to better understand the potential risks and opportunities of operational concepts to counter long-range and long-endurance air missions.

GPCAPT Andrew P Gilbert
Director, Air Power Development Centre
December 2019

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About the Air Power Development Centre

The Air Power Development Centre (APDC) was established by the Royal Australian Air Force in 1989. The APDC provides practical and effective analysis and advice on the strategic development of air and space power to the Chief of Air Force, the Royal Australian Air Force, and its partners.

The APDC mission is to support strategic decision-making about the future of air and space power for Air Force and its partners.

Air and space power is a cornerstone of Australia's security and it's unique strategic geography means that will always be so. As the principal provider of Australia's air and space power, the RAAF is tasked with the conduct of air and space operations in pursuit of the nation's security and defence. As exponents of air and space power, all members of the RAAF have an inherent responsibility to be knowledgeable regarding the theory and doctrine of air and space power.

Acknowledgements

The APDC gratefully acknowledges the document editing support provided by Warrant Officer Andrew Earl and the document formatting and publishing efforts by Mr Graeme Smith.

Beyond the Planned Air Force

The Air Power Development Centre published Beyond the Planned Air Force (BPAF) in 2017 to introduce a series of topics to extend Air Force perspectives beyond the objective force envisioned in the Defence White Paper and the Defence investment planning. Building upon the culture of innovation engendered by Plan Jericho, BPAF sought to challenge readers to explore how technological, societal, and environmental disruptors and drivers will shape Air Force's ways and means of providing air power in support of Australia's national interests. By encouraging creative and critical thinking, BPAF aims to extend the five vectors of the Air Force Strategy beyond 2027 into an uncertain future.

BPAF is not a prediction or forecast, nor is it a plan for force design beyond 2027. Instead, it aims to promote discussion as well as creative and critical thought about the future of Australian air power. It is not policy nor a roadmap but a catalyst that sparks the imaginations of airmen in envisioning the Air Force as it will evolve in an uncertain future.

BPAF was just the start; the Air Power Development Centre has embarked on a program to publish working papers that explore the possible effects of disruption on future air power.

BPAF can be accessed online at:
http://airpower.airforce.gov.au/Publications/Beyond-the-Planned-Air-Force.

About the Authors

Squadron Leader David Burningham

Squadron Leader David Burningham is the Deputy Director Doctrine Development at the Air Power Development Centre. David joined the RAAF as an airfield engineer in 1997. After postings to Canberra as a project officer, he transferred to become a Training Systems Officer and was posted to the RAAF Officer Training School. He holds tertiary degrees in building surveying, civil engineering construction, education, and military history.

As a Training Systems Officer, David was posted to a number of Air Force schools before becoming the first architect of Air Power education across the RAAF. To follow on from his air power expertise, David was posted to the Air Power Development Centre as Staff Officer Education. After a posting to Defence Force Recruiting and Directorate Personnel in Work Force Planning, David was posted back to the Air Power Development Centre as the Staff Officer Doctrine. He later assumed duties as the APDC Deputy Director Doctrine with responsibilities for managing *AAP1000-D The Air Power Manual, Edition 6 (2013),* informed the ADF development of joint doctrine, and provided the RAAF doctrine primes to support the Army and Navy development of air power doctrine.

Dr Amelia Greig

Dr Amelia Greig has degrees in Mechanical and Aerospace Engineering, and Science (majoring in Theoretical Physics) from the University of Adelaide, where she won the Most Innovative Honours Project award for the design, build and test of Australia's first atmospheric plasma thruster. She completed her PhD in Physics at the Australian National University using experiments and simulations to validate the design of a new electrothermal plasma micro-thruster, known as 'Pocket Rocket', designed for use on CubeSats. At Cal Poly, Dr Greig taught courses in spacecraft propulsion and the space environment. She also led the Aerospace Engineering Department's micro-propulsion research activities looking into new and novel micro-propulsion systems for small satellites with a focus on CubeSats. Continued work on the Pocket Rocket plasma thruster is her main research focus, with additional research into solid propellant thrusters on the horizon.

Dr Greig recently moved from California Polytechnic State University to become the Assistant Professor at the University of Texas at El Paso in the Mechanical Engineering Department and NASA MIRO Center for Space Exploration and Technology Research (cSETR) in the University of Texas at El Paso. Dr Greig is a Member of the American Institute of Aeronautics & Astronautics.

Dr Peter Layton

Dr Peter Layton, PhD is a RAAF Reserve Group Captain and a Visiting Fellow at the Griffith Asia Institute, Griffith University. He has extensive aviation and defence experience and, for his work at the Pentagon on force structure matters, was awarded the US Secretary of Defense's Exceptional Public Service Medal. He has a doctorate from the University of New South Wales on grand strategy and has taught on the topic at the Eisenhower College, US National Defence University. For his academic work, he was awarded a Fellowship to the European University Institute, Fiesole, Italy.

Dr Layton is the author of the book "Grand Strategy" and the following APDC publications:

1. (2016) CAF Paper No 5 A New Direction for Australian Air Power - Armed Unmanned Aircraft
2. (2016) A New Direction for Australian Air Power: Armed Unmanned Aircraft
3. (2018) Algorithmic Warfare: Applying Artificial Intelligence to Warfighting
4. (2018) Tomorrow's Wars
5. (2018) Prototype Warfare, Innovation and the Fourth Industrial Age
6. (2018, co-author) Australia's Antarctic National Air Power future
7. (2019, co-author) Project ASTERIA 2019 – Space Debris, Space Sustainability and Space Traffic Management

Wing Commander Michael Spencer

Wing Commander Michael Spencer is an Officer Aviation (Maritime Patrol & Response), currently serving in the Air Power Development Centre, analysing potential risks and opportunities posed by technology change drivers and disruptions to the future employment of air and space power. His operational background is with No 10 Squadron as P-3C Orion aircrew with management experiences in international military relations, operations and exercises, capability development, and project acquisitions (including the AGM-158A Joint Air-to-Surface Standoff Missile).

He is an Australian Institute of Project Management certified project manager, an Associate Fellow of the American Institute of Aeronautics & Astronautics, and member of the Australian New Zealand Space Law Interest Group. He has completed postgraduate studies in aerospace systems, aircraft weapons systems and weaponeering, information technology, project management, space mission systems, and astrophysics. He is the author of numerous APDC working papers and publications, including:

1. (2010) Pathfinder #147: Weapons in Space
2. (2017) Beyond the Planned Air Force
3. (2017, co-author) BPAF Series: Hypersonic Air Power
4. (2018) AFDN 1-19 Air-Space Integration
5. (2019, co-author) MQ-4C Triton: A Fifth Generation Air Force Disruption of Maritime Surveillance
6. (2019) Pseudosatellites: Disrupting Air Power Impermanence
7. (2019) Dragon's Jaw: the Vietnam War target that paved the way to a modern precision air weapon
8. (2019, co-author) Project ASTERIA 2019 – Space Debris, Space Sustainability, and Space Traffic Management

Glossary

A2/AD	anti-access area denial
ANP	Aircraft Nuclear Propulsion
APDC	Air Power Development Centre
BPAF	Beyond the Planned Air Force
C2	Command and control
CAMAL	Continuous Airborne Missile Air Launcher
CEP	Circular Error Probable
COA	Control of the Air
CONOPS	concept of operations
DFAT	Department of Foreign Affairs and Trade
EMI	Electro-Magnetic Interference
EO	Electro-Optical
GLONASS	Russian GLObal NAvigation Satellite System
GNC	Guidance, Navigation and Control
GPS	US Global Positioning System
HE	High explosive
HTRE	Heat Transfer Reactor Experiment
ICBM	Inter-Continental Ballistic Missile
ICT	Information communications technology
INS	Inertial Navigation System
IRBM	Intermediate Range Ballistic Missile
ISR	Intelligence, Surveillance & Reconnaissance
JASSM	Joint Air-to-Surface Standoff Missile
MJ	Mega-joules
nm	Nautical miles
NPM	Nuclear powered missile
NSC	National Security Council
NTR	Nuclear Thermal Rocket

psi	pounds per square inch
RAAF	Royal Australian Air Force
SAC	(US) Strategic Air Command
SCRAMJET	Supersonic Combustion Ramjet
SEE	Single-event effect
SLAM	Supersonic Low-Altitude Missile
SLBM	Submarine Launched Ballistic Missile
SSC-X-9	Surface-to-Surface Experimental Missile (Navy, Coastal Defence) #9.
START	Strategic Arms Reduction Treaty
TVC	Thrust Vector Control
U-235	Uranium 235 isotope
UK	United Kingdom
USSR	Union of Soviet Socialist Republics

A History of Nuclear-Engine Development

Succeeding by Failing: American and Soviet Nuclear-Powered Aircraft and Ramjet Missiles in the 1950s

Peter Layton

Introduction

The early Cold War years were a time of considerable technological change in the defence aerospace industry. Piston engines were giving way to jet turbines, attainable speeds increased almost daily, aircraft structures were increasingly streamlined, wing design was in flux, armaments were rapidly evolving and behind everything, guided missiles seemed the wave of the future. Manned aircraft, and perhaps aircraft themselves, might soon be obsolete, at least in terms of military utility.

In an era where the last major war had culminated in a technological breakthrough weapon - the atomic bomb - it seemed self-evident that strategic innovation was crucial. Such innovation, it was both hoped and feared, would usher in new technologies that would revolutionise warfare and make the nation that created them victors in the Cold War between the US and the USSR.

The US began actively investigating a broad sweep of technologies with one major stream being in nuclear engine research. Within this were three focus areas: nuclear turbojets for manned bombers (Aircraft Nuclear Propulsion 1951-1961); nuclear rockets for manned space missions (Project Rover 1955-1973); and nuclear ramjets for unmanned bombers or cruise missiles (Project Pluto 1957-1964). All three programmes shared the key technical idea that a nuclear reactor could replace the combustion chamber of an internal combustion engine.[1] Informing the overall push was the 1948 Lexington Project report commissioned by the US Atomic Energy Commission that determined the level of technical difficulty in ascending order were Aircraft Nuclear Propulsion (ANP), Project Pluto and Project Rover.[2]

In being air-breathing systems, ANP and Project Pluto are worth examining in more detail not just from a technical perspective but also concerning managing strategic innovation in a time of rapid technological change. This discussion looks initially at the context of the time, secondly the ANP programme that saw an aircraft flown, thirdly Project Pluto where a nuclear-ramjet was tested and lastly at the reasons for the demise in the early 1960s of continuing considering using nuclear energy for aircraft or missile propulsion.

A threatening context

The months from August 1949 to June 1950 created a widely held fear of a looming great power war. In August 1949, the USSR tested its first atomic bomb, in October 1949 communists captured power in China, in April 1950 a US National Security Council (NSC) policy paper, NSC-68, determined the USSR was a clear and present danger requiring a massive US defence build-up, and in June 1950 the Korean War started.[3] NSC-68 considered 1954 was "the year of maximum danger" when war with the USSR was likely.[4]

The cost of responding to the perceived threat so soon after World War II appeared overwhelming, hence the favoured approach became maximising the gains from the sizeable US qualitative and quantitative lead in atomic weapons. Technology would replace manpower on future battlefields with the critical centre of gravity being the Soviet heartland where its military-industrial capabilities lay.[5] The best US military solution seemed to be intercontinental air power striking deep into the USSR; 'intercontinental' as allied airbases closer to the USSR seemed easy targets for Soviet atomic weapons in time of war. Accordingly, USAF's Strategic Air Command (SAC) was greatly expanded. SAC grew from some 300 bombers and 50,000 personnel in 1946 to 1650 bombers and 224,000 personnel in 1956. The USAF overall was allocated about half the US defence budget across these years.[6]

SAC relied on manned long-range bombers and these were becoming vulnerable to modern air defence networks, supersonic fighters and emerging surface-to-air-missile systems. The older B-29 Superfortress bombers were replaced by the B-36 Peacemakers, the B-47 Stratojets and these, in turn were replaced by B-52 Stratofortress bombers. A new nuclear weapon delivery system seemed necessary but what that should be was very uncertain. On the other hand, the generous defence budget funding now allowed numerous possibilities to be considered.

The issue was then dramatically clouded by the invention of thermonuclear weapons, heralded by a US test in October 1952 and a Soviet one in August 1953. The new hydrogen bombs were hugely more destructive than atomic weapons, significantly upping the geostrategic stakes and suggesting a wrong technological choice in acquiring a new nuclear delivery system could be fatal.[7]

In early 1955 there were US developmental contracts underway for the: B-58 Hustler bomber; the WS-110A chemical bomber (that would become the XB-70 Valkyrie); the WS-125A nuclear-powered bomber; the subsonic Snark cruise missile; the Navaho Mach 3 cruise missile; the Atlas ICBM and the Titan backup ICBM.[8] This lengthy list would quickly grow to include Project Pluto, the Dynasoar hypersonic skip-glide spacecraft, the Thor and Jupiter IRBMs, Polaris and Atlantis SLBMs, and the Minuteman ICBM.[9]

Nuclear-powered aircraft

In broad terms USAF's operational requirements for a nuclear-powered bomber were straightforward: an unrefueled range of about 10,000 nm, operate at altitudes between 60,000 to 75,000 feet, and have 'the maximum speed possible'.[10] Nuclear propulsion appeared to offer significant advantages in potentially giving almost unlimited range and endurance; some suggested at least a week airborne.[11] Nuclear-powered aircraft would not need to rely on vulnerable overseas bases or air-to-air refuelling and would be perfect for airborne alert tasks. Such aircraft though would still need to be survivable in the face of enemy defence systems and be affordable. The technical challenges were readily apparent in that a small, lightweight nuclear reactor was essential, sufficient engine thrust was required to meet the atomic strike mission's speed and payload requirements and crew nuclear safety was a real issue. USAF accordingly tentatively planned on having the initial nuclear-powered bomber force enter service around 1966 to 1969.[12]

The idea of using nuclear power for aircraft propulsion originated around 1944 with a research program on reactor technologies and engine transfer systems beginning in mid-1946. In 1951, these studies resulted in a proposal to actively develop nuclear propulsion for manned aircraft. Three main elements were then contracted: the two X-6 prototype test aircraft, the nuclear propulsion system (reactor and turbojets) and the NB-36H reactor flight-test aircraft.

Convair received the US government X-6 contract. The aircraft was envisaged as being of comparable size to the company's B-36 Peacemaker bomber with a length of 50m, a wingspan of 70m and an empty weight of some 100 tonnes. The X-6 was planned to have 12 turbojets; eight conventionally fuelled used for take-off and landing, and four nuclear-powered used during in-flight trials. This was an ambitious but expensive test program and was cancelled by the in-coming Eisenhower administration in 1953 on budgetary grounds. However, the other two elements continued.[13]

General Electric was awarded the propulsion contract, progressively developing across 1955-1961 three direct-cycle nuclear power plants under the ground-based Heat Transfer Reactor Experiment (HTRE) test-rig program. The final HTRE-3 propulsion system featured a solid moderator using lightweight hybrided (sic) zirconium instead of water, a horizontal reactor to meet aircraft carriage requirements and produced sufficient heat to power two X-39-5 (modified J-47) turbojets simultaneously. HTRE-3 had several firsts including demonstrating an all-nuclear turbojet start, having a primary shield able to handle radiation levels expected in flight and in being designed for in-flight stresses, air pressures, temperatures and G loadings.[14]

The third element was to flight test a reactor. In mid-1952, Convair was contracted to modify two B-36 aircraft: one for ground test, the other for flight test and designated as the NB-36H nuclear-powered bombers. The major modifications involved firstly, the crew compartment and avionic cabin being replaced by an 11 tonne nose section lined with lead and rubber to protect against reactor radiation and secondly, the rear internal bomb bay being altered to allow fitment of the 16 tonne reactor. Less apparent were the cockpit glass transparencies being some 30 cm thick and nine water-filled shield tanks in the fuselage to absorb any escaping radiation. [15]

The NB-36H made 47 flights during the period July 1955 to March 1957, with the reactor going critical for the first time in flight in September 1955. The reactor did not power the aircraft, instead being tested to verify the feasibility of a safe sustained nuclear reaction on a moving platform. For each NB-36 flight, the one-megawatt reactor was winched up into the bomb bay at a dedicated pit at the Convair Fort Worth plant and then removed again after landing.[16] When in flight, the aircraft was accompanied by a radiation-monitoring B-50 Superfortress (a slightly updated B-29 Superfortress) and a C-119 Flying Boxcar transport aircraft carrying paratroopers able to be dropped to secure any crash site and limit bystander exposure to radiation.[17]

Figure 1: NB-36H Peacemaker experimental nuclear propelled aircraft[18]

The results of the nuclear propulsion tests and the NB-36H were mixed. HTRE-3 had proven nuclear-power turbojet feasible and that a flyable propulsion unit could be built albeit technical challenges remained. However, the primary difficulty of being able to build a nuclear reactor small enough to fit to aircraft while producing operationally significant energy output continued. It seemed using the contemporary technology would mean nuclear-powered aircraft were relatively slow. For a time concepts of 'nuclear cruise, chemical dash' were investigated; supplemental aviation fuel would allow supersonic dash in the target area.[19]

The NB-36H flight programme further highlighted the hazards associated with operating nuclear-powered aircraft. While well-shielded aircraft would not normally pose radiation dangers to air or ground crew, there were worries that accidents and crashes might release fission products from the reactors, and about the dosage from prolonged human exposure to leakage radioactivity.[20] In this, the flights mainly served to draw attention to the real difficulties that would arise in working with nuclear fuel in operational service conditions.[21]

NB-36H testing finished in 1957 while research on aircraft nuclear propulsion continued, finally ceasing in 1961 when the new Kennedy administration reallocated funding. However, there remained occasional flickers of renewed interest. The Continuous Airborne Missile Air Launcher (CAMAL) concept led to Dromedary, a turboprop design capable of an airborne alert for up to 70 to 100 hours and able to launch the AGM-48/GAM-87 Skybolt medium-range ballistic missile.[22] The US Navy also occasionally expressed interest in a nuclear-powered turboprop flying-boat for long-endurance reconnaissance and early-warning missions. At one stage, it seemed the UK might sell three mothballed Princess-class flying boats to the USN for nuclear-power trials but funding was not forthcoming.[23]

Further afield, the USSR was also busy. In the late 1950's Tupolev's OKB-156 designed but did not build two nuclear-powered bombers: the subsonic Tu-119 and supersonic Tu-120. The Soviet leadership thought the projected payloads and speed were inadequate for the costs involved. Tupolev was though authorized to continue research on nuclear aircraft.[24] Accordingly, a Tu-95 turboprop bomber was modified at a nuclear complex near Semipalatinsk in Kazakhstan to allow flying a nuclear reactor, becoming the Tu-95LAL (Letayushchaya atomnaya laboratorya – flying atomic laboratory[25]). Mirroring the NB-36H development trials, some 34 Tu-95LAL flights were undertaken in 1961 with the reactor on board but without providing propulsion. The tests similarly revealed that a nuclear-powered aircraft was impractical with the technology of the time. The gain in performance from not carrying fuel was consumed by the heavy reactor and shields and so Soviet interest in nuclear-powered aircraft declined.[26]

Nuclear-powered Pluto

As USAF interest in nuclear-powered bombers waned, the US focus shifted to nuclear-powered air-breathing missiles. In 1957, studies suggested that a US nuclear ramjet powered missile might be able to be built that could fly at low altitude at speeds of about Mach 3 and deliver a 3 to 4 tonne payload at intercontinental ranges.[27] This Supersonic Low Altitude Missile (SLAM) was envisaged as being about 27m long and weighing around

27.5 tonnes (about 60,800 lbs). There were hopes that with development the missile could be fired from road-mobile launchers, enhancing system survivability.

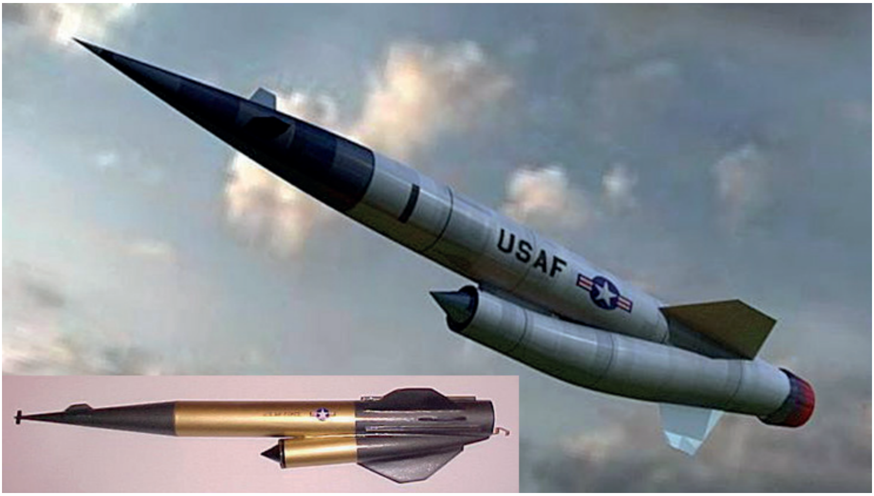

Figure 2. US Supersonic Low-Altitude Missile.[28]

Nuclear ramjet propulsion systems were primarily attractive because of their very long range compared to conventionally powered ramjets of the same weight, including fuel. However, the Project Pluto Director cautioned that:

> "Contrary to popular belief, this range is not infinite. Several factors can limit the life of a reactor for ramjet applications to periods of time from a few hours to a few days depending on the methods of construction. The most obvious limit is actual [uranium] fuel consumption".[29]

For a fully developed Pluto it seems the range would have been about 20,000 nm (37,000km).

In order to reach the ramjet's operating speed, SLAM would be launched using a cluster of conventional rocket boosters. When at its cruising altitude of 35,000 ft and distant from populated areas, the nuclear reactor would be turned on and go critical – ideally when over enemy territory. Since nuclear power gave it extended range, the missile could cruise in circles over the ocean until ordered by radio signal to descend and fly at 1000 ft above ground level for a Mach 2.8 to 3.0 dash to the target areas. SLAM's high speed at low altitude made defensive systems ineffective and so the missile could use its long range to overfly and drop thermonuclear bombs on 16 widely separated targets.[30]

The key was again the engine: a ramjet that used nuclear fission to superheat incoming air instead of using chemical fuel. This heat came from a 600-megawatt air- cooled reactor, a squat cylinder 1.5m in diameter and 1.5 m long. Initially intended to have a ten-hour lifetime, the reactor core would comprise tens of thousands of ceramic fuel elements incorporating a homogenous mixture of beryllium oxide and highly enriched uranium dioxide. Ceramics were required to withstand the design operating temperatures of up to 1,400°C.[31] Intended for unmanned use, the in-service reactor was planned to not include radiation shielding for the fission products of neutrons and gamma rays.[32] Missile subsystems and in particular the avionics needed designing accordingly.

The Lawrence Livermore National Laboratory won the contract to develop the engine, code named 'Pluto', which also became SLAM's nickname. Project Pluto produced two working nuclear ramjet engine prototypes: the Tory-IIA and the Tory- IIC, both successfully tested in the Nevada desert.

Tory II-A's first operation was in mid-May 1961. The test firing lasted 45 seconds at 40 megawatts (roughly 25 per cent of maximum power), equivalent to about 2,000 pounds of thrust. Upgrading test facilities for full-power tests took several months, but in September and October three tests in rapid succession at 150 megawatts made Tory II-A "a resounding success" albeit far too large for the intended purpose.[33] Three years later, the follow-up flight-ready size and weight Tory II-C was installed and tested in the rig. Tory II-C's full-power run in late May 1964 produced 513 megawatts and the equivalent of over 35,000 lbs of thrust. Tory-IIC ran for as long as five minutes during test runs in 1964 and, in offering a realistic design, appeared close to being ready to fly.[34]

Airframe design had not though kept up with the ramjet engine trials. The environment at Mach 3 at sea-level was particularly harsh with skin temperatures of 500°C and sound pressure levels of around 162 decibels. Some 1600 hours of wind tunnel testing had resulted in a canard configuration design with a scoop type inlet but further detailed design was needed. Of interest, the forward sections of the missile were envisaged as being gold-plated to dissipate heat by radiation.[35] However, if SLAM had been built there was real uncertainty about how to safely test-fly a missile with a highly radioactive propulsion system.

SLAM did not use radiation shielding so as to lower overall missile weight and maximise performance. Accordingly, the reactor when it went critical emitted intense radiation beyond the missile itself. However, it was considered that the missile would fly too fast to expose humans underneath to the prolonged radiation necessary to induce radiation sickness. Only a relatively low neutron population would reach the ground per kilometre, for a vehicle travelling at several hundred meters/ second.[36]

There was an additional problem in that in-flight the nuclear ramjet would have emitted fusion products in its exhaust. In being widely distributed, as the missile cruised, these products were considered likely to present only marginal dangers to humans. Even so, there were definite safety concerns, particularly when missile flight-testing over US territory was considered.[37] Moreover, the pressure wave from a low flying Mach 3 missile would have been significant, probably sufficient to damage light structures on the ground underneath. The surface noise levels of a passing Pluto were estimated at 150 decibels also potentially posing human hearing risks.

To avoid these issues, one idea was to fly Pluto in a figure of eight pattern around the US Pacific territory of Wake island, finally diving the missile with its highly radioactive reactor into an adjacent 20,000ft deep oceanic trench when testing concluded. On 1 July 1964, after some seven and a half years work Project Pluto was cancelled by the US Atomic Energy Commission and the USAF.[38]

Success in Failure

The considerable effort and funds expended in the ANP and Project Pluto yielded much technical information and engineering expertise but ultimately little else. This was not for lack of enthusiasm in the defence aerospace industry about the possibilities. In 1957, Kelly Johnson of Lockheed's Skunk Works fame, wrote that:

> "After a half century of striving to make aircraft carry reasonable loads farther and farther, the advent of a type of power plant that will solve the range problem is of the utmost importance…. this unique characteristic is one to be greeted enthusiastically".[39]

In terms of engineering, numerous technical challenges remained for both nuclear- powered aircraft and missiles but undoubtedly could have been solved. Less easy was addressing the inherent radiation hazards associated with nuclear energy. The heavy shielding required on human safety grounds was inherently incompatible with the lightweight materials needed for aircraft structures. Moreover, a serious accident with a nuclear-powered aircraft or missile could have left the crash site uninhabitable for many years.

Such issues were not though the principal reasons why the ANP and Pluto were seemingly suddenly terminated. Instead it was the consequences arising from the development of thermonuclear weapons. Compared to atomic weapons, thermonuclear weapons could be relatively smaller in explosive yield but give greatly increased destructive power. In this, hydrogen bombs both made strategic weapon systems crucial to national power while solving a major technological problem.

Investigating atomic options for strategic innovation

The US was actively investigating a wide range of atomic weapon delivery systems in the 1950s, as discussed earlier. The geostrategic circumstances required strategic innovation but US resources and funds were limited. The approach taken to research multiple options concurrently, ranging from crewed long-range strategic bombers, long-range cruise missiles, ICBMs, to hypersonic skip-glide spacecraft, was undoubtedly costly but gave the desired flexibility to deal with the considerable technological uncertainties of the time.

This type of strategic innovation management approach - termed Type II Flexibility - involves investing in the development of many different new technology systems up to the point they can be tested, evaluated and acquisition data determined.[40] This investment buys information and a realistic option to proceed further when desired or uncertainties are resolved. In discussing this hedging approach, Stephen Rosen writes:

> "Large scale procurement is deferred…to allow uncertainties to work themselves out. When long-term uncertainties become short-term requirements, decision makers can choose from an array of prototypes the system best suited to the needs of the day."[41]

Civilian physicists, in solving the puzzle of how to make a thermonuclear weapon, also solved the puzzle for choosing which of the numerous aircraft and missile options to bring forward into mass production and operational service. ICBMs suddenly became practical weapons of war as warhead weight estimates went down from 4.5 tonnes to 0.7 tonnes and terminal accuracy required increased from 0.5km to 4-6km. The increased damage radius of smaller-sized high-yield thermonuclear warheads made navigation accuracy less important for their delivery by payload-carrying missiles.

By the mid-1950s when thermonuclear weapons arrived, the technological challenges with ICBMs had mostly been solved. They were at a technological readiness level appropriate to advance into full-scale production. ICBMs met operational requirements for very fast, highly survivable intercontinental strike considerably better than any other option being investigated. There was no strategic need to develop the alternatives further.

Conclusion

Nuclear-powered aircraft and ramjet missiles in comparison to ICBMs were simply less cost-effective. Indeed, they continued to be funded as research projects mainly because governments found it hard to cut off money completely given vocal support by small groups of enthusiasts. This lobbying lay behind the timing of the major funding cuts when US Presidential administrations changed.

In terms of strategic innovation the ANP and Project Pluto were successful as they produced the information needed to allow prudent decisions to be made in US national defence programs. They ultimately proved a technological dead-end, even if the dream of a nuclear-propelled aircraft with almost unlimited range and endurance remains appealing. It can be reasonably said that in failing, the Aircraft Nuclear Propulsion and Pluto projects succeeded.

Endnotes

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Fundamentals of Nuclear-Powered Engines

Engines make it Fast; Nuclear makes it Last!

Amelia Greig

Introduction

The purpose of a propulsion system is to convert stored energy into kinetic energy to produce a force or thrust. In accordance with Newton's third law, 'for every action there is an equal but opposite reaction'[1], the thrust propels the engine, and anything rigidly attached to it, forward. The word 'propulsion' in fact derives from two Latin words: 'pro' meaning before or forwards and 'pellere' meaning to drive.[2] The pursuit of increased mission capabilities with different requirement for altitude, range, speed, and manoeuvrability, has driven engineers to pursue new and innovative propulsion system designs.

Aeronautical propulsion systems have progressed from piston engines, through hydrocarbon fuel based turbine (jet) engines, to upper atmospheric supersonic scramjet engines, all relying on hydrocarbon fuel-based combustion for energy. Parallel to these efforts were the development of hydrocarbon fuel based solid, liquid, and hybrid rocket engines. Each engine offers different advantages and disadvantages, necessitating trade-offs for the final system design to balance requirements for operating speed, altitude, payload weight, and endurance. A key limitation of fuel-burning propulsion systems is the need to integrate on-board storage and plumbing systems for the propellant, adding to the mass burden of the total system design.

The nuclear engine offers an alternative to hydrocarbon combustion engines that can significantly improve operating range and endurance of an air vehicle. By removing the consumption of an on-board combustible fuel source, nuclear engines do not require refuelling and can operate for significantly longer durations. The on-board fuel mass is reduced but additional mass is required for adequate radiation shielding. Without adequate shielding, nuclear engines pose an ongoing threat to nearby biological tissue and the environment.

Fundamentals of Propulsion Systems

Aeronautical propulsion works on the simple principle that if some amount of mass is expelled with some velocity from the rear of the flight vehicle then, by conservation of momentum, the vehicle moves in the opposite direction, or forward. The higher the mass expelled from the rear of the vehicle, or the higher the exhaust velocity of the expelled mass, the higher the opposing force transfer to the air vehicle.

The most common type of propulsion system is thermal propulsion, where heated propellant in gaseous form is expelled from the rear of a vehicle to produce forward motion. As part of the exhaust process, the hot exhaust gases are expanded through a nozzle that is shaped to maximize the directional velocity attained by the exhaust, maximizing engine performance. The higher the temperature of the exhaust gases the higher the resultant exhaust velocity from the nozzle and the higher the resulting thrust achieved by the engine. For the same temperature, light elements such as hydrogen gain higher exhaust velocities than heavier elements such as oxygen.

The two most common types of thermal propulsion for aeronautic applications are the air-breathing jet and the rocket.

1. **Air-Breathing Jet**: An open inlet duct in which in air from the ambient environment is heated before being expelled as hot exhaust for thrust (refer Figure 1: Air-breathing jet engine schematic and photo.).

2. **Rocket**: A closed inlet system that carries all propellant on-board. The propellant is heated before being expelled as hot exhaust for thrust (refer Figure 2).

As rockets require all propellant be carried on-board, they require larger supporting structures than air-breathing jet engines but can operate at any altitude or in space. Air-breathing jets can only operate at altitudes where there is sufficient atmosphere to maintain the required air flow rates. Total thrust of air-breathing jet engines is defined by the inlet collection area limiting the mass flow rate of air, whereas rockets use pressurized storage tanks and high-flow rate turbomachinery to achieve much higher mass flow rates and total thrust.

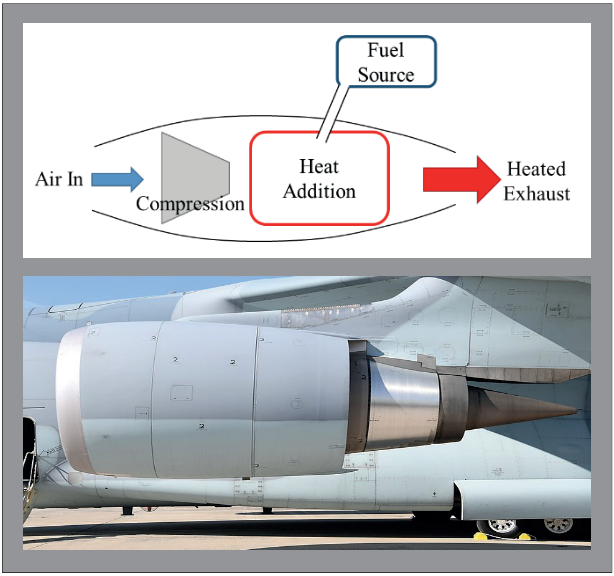

Figure 1: Air-breathing jet engine schematic[3] and photo.[4]

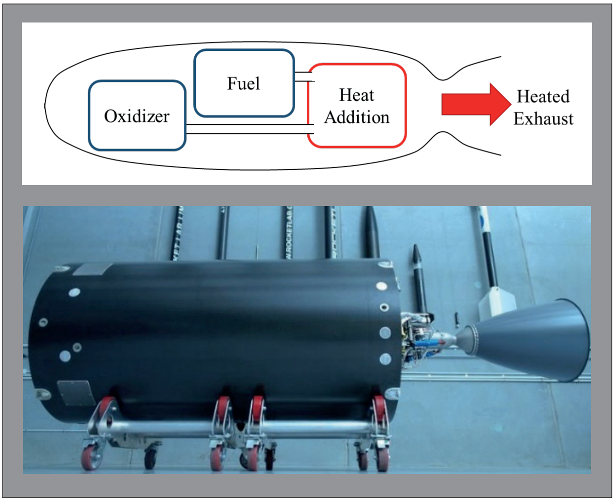

Figure 2. Rocket-engine schematic[5] and photo.[6]

Nuclear propulsion systems can take the form of either an air-breathing jet or a rocket. The different types of nuclear engines are explored further later in this chapter. First, to understand the application, technology, and performance of nuclear propulsion, key concepts as they are used here are introduced.

1. **Mission:** The complete flight, from take-off or launch to final destination.
2. **Range**: The distance covered during a mission.
3. **Thrust**: The instantaneous force applied by the propulsion system. Thrust by itself does not give any indication of range nor how much mass can be moved over the range.
4. **Burn Time**: How long the propulsion system provides thrust. Total burn time is how long the propulsion system produces thrust if it consumes all on-board propellant.
5. **Total Impulse**: Combines thrust and total burn time to indicate the maximum range for a given vehicle mass.
6. **Specific Impulse**: Thrust produced per mass of propellant consumed. Similar in concept to propellant efficiency. A higher specific impulse means lower propellant consumption for a particular mission, giving overall lower system masses and cost savings. Unlike thrust that can usually be increased by increasing engine size or propellant flow rates, specific impulse is limited by the energy extraction technique.
7. **Specific Thrust**: Thrust produced per mass of air inflow to a jet engine. Similar concept to specific impulse, but specifically for air-breathing propulsion systems.
8. **Terminal Velocity**: Maximum achieved speed of the vehicle. Determined from vehicle mass, thrust, burn time, and ambient conditions (eg atmospheric drag).

9. **Trajectory or Flight Path**: The path of an object during flight. When undergoing powered flight the trajectory is fully controllable.

10. **Ballistic Trajectory**: The path of an object accelerating under the force of gravity alone. Ballistic trajectories follow parabolic paths that are well defined and predictable. Any vehicle that ceases powered flight will enter a ballistic trajectory from that point onward.

A simplified visualisation highlighting the key differences between a powered flight trajectory and a ballistic trajectory is depicted in Figure 3.

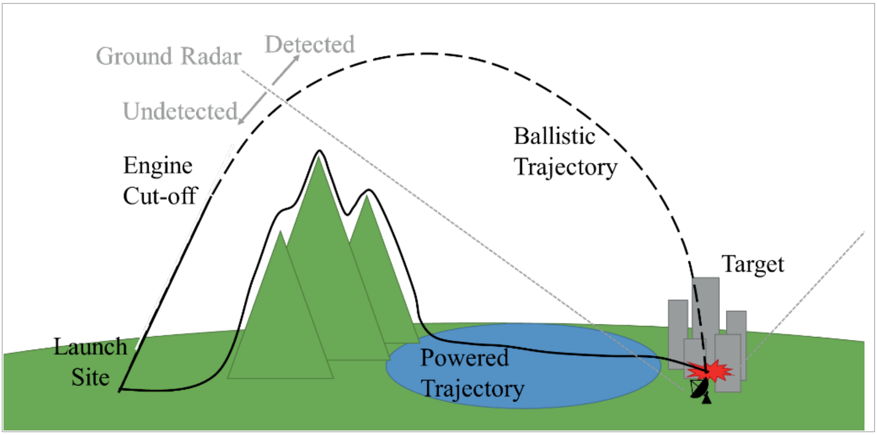

Figure 3: Comparison of powered flight and ballistic trajectories.[7]

Chemical Thermal Propulsion from an Atomic Perspective

Currently, most air-breathing jets and rockets use **chemical potential energy**[8] to produce the heat required for thermal propulsion. Chemical potential energy is stored in the chemical bonds within any molecule or compound. These bonds are formed by the **electromagnetic fundamental force**[9], and when broken the energy is released. Energy cannot be created or destroyed, so when released the chemical energy goes into other forms of energy such as heat.

Combustion is one method to break the chemical bonds within molecules. During combustion, an oxidizer (containing oxygen) and a fuel (containing hydrogen) react, breaking the original chemical bonds and forming new bonds. If the new bonds have lower combined chemical energy than the original bonds, the excess energy is released as heat. This is called an exothermic reaction and results in heated by-products.

The heated by-products increase the local pressure in the combustion chamber forcing the hot gases to exit the combustion chamber and expand through the nozzle. As the gas expands, heat energy is converted to kinetic energy, or the energy of movement, increasing the velocity of the exhaust gases. The result is a high momentum exhaust plume that imparts a corresponding high thrust on the engine. The process of converting energy from internal potential chemical energy to kinetic energy is summarised in Figure 4.

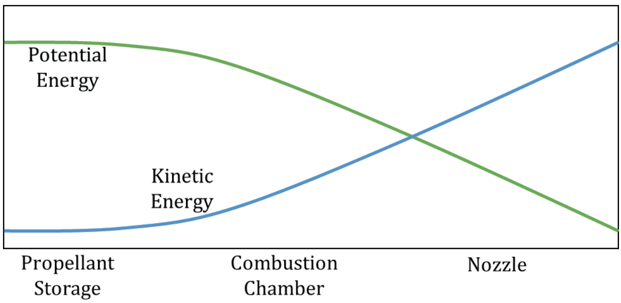

Figure 4. Process of converting propellant chemical potential energy to exhaust kinetic energy.[10]

The total energy available in the chemical bonds depends on the propellants used. Each different molecule or compound has a different arrangement of atoms, each bound with a different bond strength. The energy density available from a combustion reaction is the total energy of all chemical bonds in the oxidizer and fuel, less that energy of the bonds formed in the combustion by products. Table 1 gives examples of the **energy**

density[11] in common chemical propulsion reactions. The higher the energy density the higher the resultant exhaust velocity and thrust. The highest chemical energy density currently known is Lithium and Fluorine at 23.75 mega-joules per kilogram (MJ/kg). However, the reaction is very unstable and the propellants highly volatile, so the Hydrolox reaction between Hydrogen (H_2) and Oxygen (O_2) containing 13.4 MJ/kg is most commonly used.

Propellant Combination	Specific Energy (MJ/kg)[12]
Lithium + Fluorine	23.75
Hydrogen + Oxygen (Hydrolox)	13.4
Nitroglycerin	6.38
Thermite (powder Al + Fe_2O_3 as oxidizer)	4.00
Hydrogen peroxide decomposition (as monopropellant)	2.7
Hydrazine decomposition (as monopropellant)	1.6

Table 1. Example energy storage densities for common chemical propulsion reactions.

Chemical Thermal Propulsion Engines

Chemical air-breathing jets come in a number of different design variations. The most common is the turbine engine but higher flight speeds can be achieved using ramjets or scramjets.

A **turbine engine**[13] has an open inlet that uses oxygen in the ambient air as the oxidizer. Air is drawn into the engine and compressed by a physical compressor to increase the local pressure. Upon entering the combustion chamber, the compressed air mixes with an on-board hydrocarbon fuel supply at the correct ratio for optimal combustion. The hot combustion gases pass through a turbine that extracts enough energy from the flow to power the compressor, before expanding through a nozzle to produce thrust. Figure 5 shows the layout and components of a generic turbine engine.

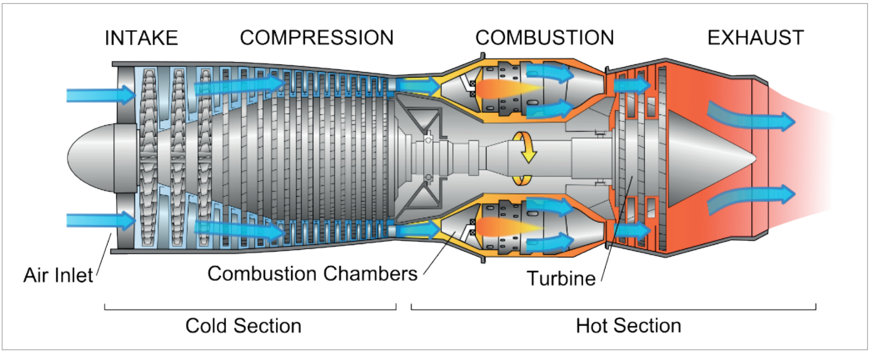

Figure 5. Turbine engine.[14]

Air compression and combustion in a turbine engine must occur at subsonic speeds well below Mach 1. Aircraft using turbine engines may have flight speeds close to or above Mach 1, in which case the inlet must slow the air prior to entering the compressor. At flight speeds greater than around Mach 2, the act of slowing the incoming air flow to subsonic speeds causes overheating of the precision manufactured compressor blades. To achieve flight speeds over Mach 2, the physical compressor and associated turbine are removed and an extended inlet duct is used instead to slow and compress the air flow to subsonic speeds for combustion. This type of engine is called a **Ramjet**[15], shown in Figure 6. Generic ramjet engine, named for the ram effect that slows the inlet air.

A ramjet requires forward motion to collect and compress the air for combustion. With the removal of the physical compressor, a ramjet cannot draw air in by itself so needs a supplementary propulsion system to first accelerate the air vehicle to high flight velocities for operation. A **turboramjet**[16] is a hybrid design for an integrated turbine/ramjet engine. While stationary and at low speeds, a physical compressor works to draw in and compress the inlet air. Once high flight velocities over Mach 2 are reached, bypass ducts open that redirects the inlet air around the physical compressor while compressing the air through the ram effect at the same time. Through this method, the same combustion chamber and nozzle can be used for both the low speed and high speed propulsion systems minimizing system size and mass.

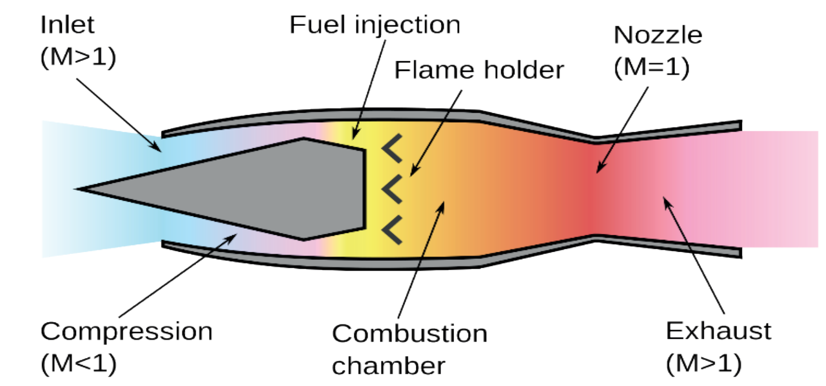

Figure 6. Generic ramjet engine.[17]

A ramjet operates up to hypersonic flight speeds (ie Mach 5+). Above around Mach 5, the temperature increase from slowing the inlet air to subsonic speeds for combustion will damage or even melt the duct or airframe. To overcome this limitation and achieve hypersonic flight conditions using air-breathing propulsion, the combustion must now occur at supersonic flow speeds. A **scramjet**[18] (Supersonic Combustion Ramjet), shown in Figure 7. Generic scramjet engine, is the result. Supersonic combustion is a complex process and challenges with combustion instabilities plague current scramjet operations. As for the ramjet, a scramjet cannot operate at subsonic or low supersonic speeds and needs a booster engine or vehicle to first accelerate the engine to operational speeds.

Another option for hypersonic vehicles is to use rockets. There is no ambient air intake for rockets negating the corresponding temperature challenges from slowing the incoming air and the combustion instabilities associated with supersonic combustion. Rockets are the most versatile engine in regards to air speed, as the internal propellant storage and controlled feed system means they are capable of operating in the same configuration from stationary conditions through to hypersonic speeds. Chemical rocket propulsion depends on the use of liquid, gaseous, or solid propellants.

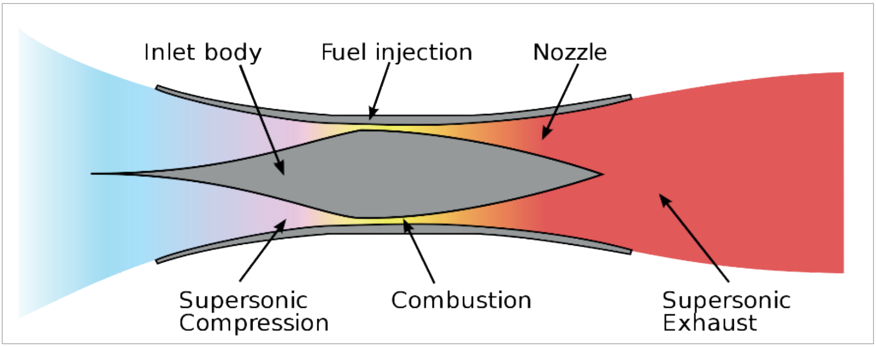

Figure 7. Generic scramjet engine.[19]

A **solid rocket**[20] (refer Figure 8. Generic solid rocket.) contains both the fuel and oxidizer held together by a binder material in a single solid propellant grain. The solid propellant grain lies inside the combustion chamber and burns to produce hot gases throughout the combustion process. The hot exhaust gases expand through the nozzle for thrust. As the fuel and oxidizer exist in a single grain, once ignited it is difficult to stop the burn process and most solid rockets are treated as single burn engines. Solid rockets are the most compact and have the simplest construction of all thermal rocket engines, but also have the lowest specific impulse of chemical rockets at around 200 seconds.

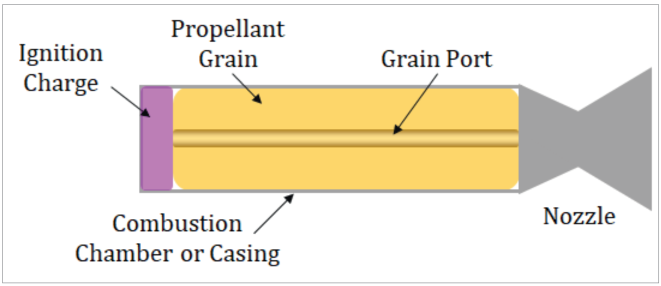

Figure 8. Generic solid rocket.[21]

Liquid or gaseous rockets[22] (refer Figure 9) provide higher thrust levels compared to solid rockets, and having restart capability give more advanced mission control. Storing separated propellants in liquid or gaseous form and feeding them into the combustion chamber using controllable flow systems permits high flow rates, precise combustion control, and start/stop capabilities by pausing propellant flow. The controllable propellant feed and ability to use the Hydrolox reaction gives the highest specific impulse capabilities of chemical rocket engines, up to 420 seconds.

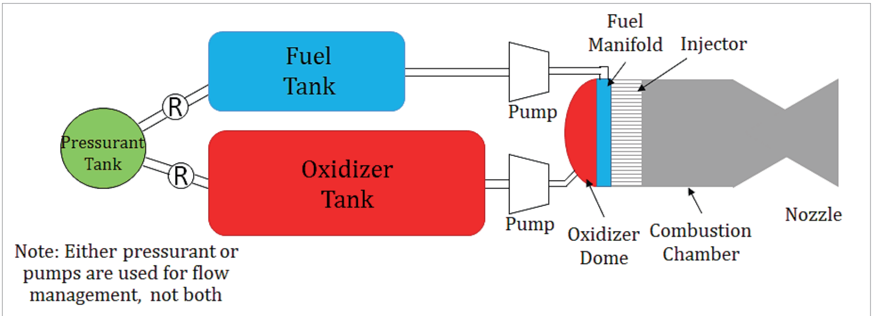

Figure 9. Generic liquid rocket.[23]

Hybrid rockets[24] (refer Figure 10) are a combination of liquid or gaseous rockets and solid rockets. One propellant (usually fuel) is in solid grain form, with the other (usually oxidizer) in liquid or gas form and pumped into the combustion chamber. Hybrid rockets have the controllability of liquid rockets, but are not as powerful and have less specific impulses of around 300 s as they cannot use the Hydrolox reaction. Having one propellant in a separate storage tank they are smaller than liquid rockets but larger than solid rockets. Being between liquid and solid rockets in most performance metrics, hybrid rockets are often used only as educational tools. Having separated propellants means they are safer than solid rockets, but still retain the complexity of a liquid or gaseous propellant feed system.

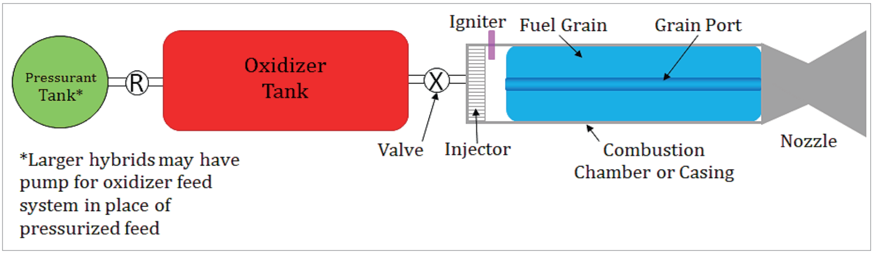

Figure 10. Generic hybrid rocket.[25]

Chemical thermal engines are available in a wide variety of designs, each with different benefits and draw backs. At this stage of development, energy extraction from chemical combustion is at its physical limits, meaning specific impulses are as high as they can be. Higher thrust or increased range can be attained, but only by increasing system size, which is currently limited by structural capabilities of materials. For the next stage of thermal propulsion development, alternate energy sources must be investigated.

Nuclear Thermal Propulsion from an Atomic Perspective

The potential energy stored in chemical bonds can appear quite energetic on the macroscopic scale, and when combined with high mass flow rates can make incredibly powerful missiles, aircraft, and rockets (refer Figure 11). However, on the particle level the electromagnetic force involved in chemical potential energy is relatively weak. To find a higher density energy fuel source we need to look deeper within particles.

Within any atom there are subatomic particles called protons, neutrons, and electrons. The protons and neutrons bind together to form a central nucleus, with the smaller electrons forming a cloud around the nucleus. The force binding the protons and neutrons together in the nucleus is called the **Strong Nuclear Force**[26], and is currently the strongest known physical force in the Universe.

Figure 11. Powerful chemical rocket launch.

Because the nuclear force is so strong, it is also quite difficult to break. To date, only certain elements are capable of nuclear splitting or **nuclear fission**[27], and are hence known as fissionable materials. Uranium-235 is one example of a fissionable material. Fissionable materials form unstable isotopes, where the number of particles in the nucleus causes an imbalance in the atomic structure. An unstable atomic nucleus may naturally split into two smaller fragments in a process called spontaneous fission. Spontaneous fission occurs too slowly to make use of the released energy for propulsion. To output energy at higher rates, the fission process is artificially incited, accelerated, and controlled using a nuclear fission reactor.

Within a **nuclear fission reactor**[28], such as the one shown in Figure 12, fuel rods containing a stable fissionable material such as Uranium-235 are centrally housed. Free neutrons fired into the fuel rods are absorbed by the stable Uranium-235 atoms, turning them into unstable Uranium-236 isotopes. The unstable isotopes fission into two smaller fragments that have a combined nuclear binding energy less than the original Uranium-235 nucleus. The excess energy is released as additional energetic neutrons and radiation. The fission reaction is illustrated in Figure 13.

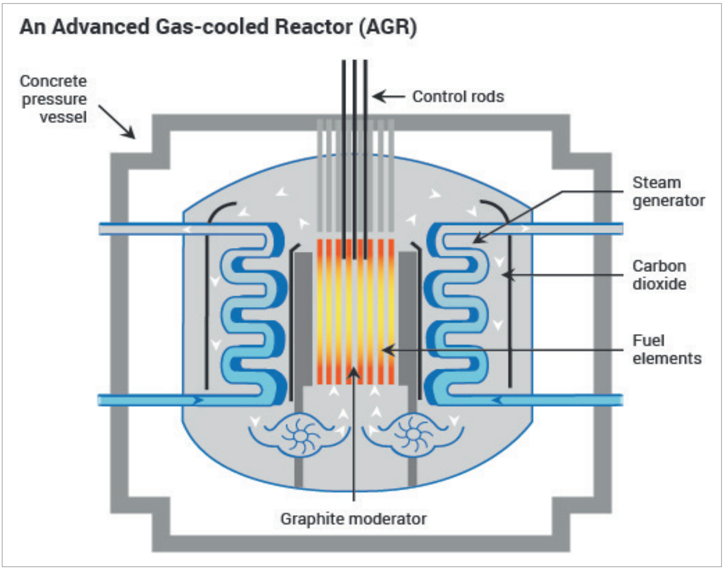

Figure 12. Example of a nuclear fission reactor.[29]

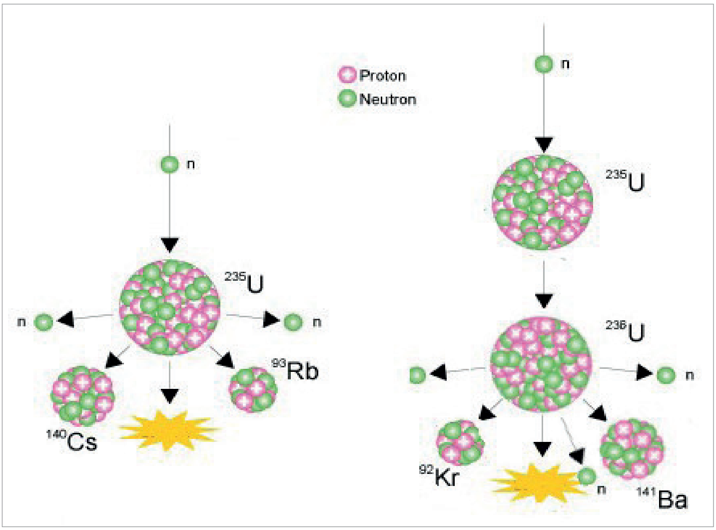

Figure 13. Nuclear fission reaction releasing energy.[30]

A neutron moderator, such as water or graphite, slows the emitted fission neutrons to energies capable of being absorbed by the surrounding stable Uranium-235 atoms, inciting a self-sustaining chain reaction of fission events. The rate of fission is controlled using control rods or rotating control surfaces containing boron or beryllium. Boron readily absorbs neutrons but is not fissionable, slowing the fission reaction. Beryllium reflects neutrons, so when placed around the outside of a reactor reflects escaping neutrons back towards the fuel rods increasing the fission reaction rate.

Energy released during fission that is not used to sustain the fission reaction is converted to heat through particle collisions. The heat can be used to increase the temperature of a working fluid for heat exchange or converted to electrical energy using a thermoelectric generator.

The energy density of Uranium-235 fission is 144,000,000 MJ/kg of pure Uranium-235 isotope.[31] Comparing this to the highest usable chemical energy density of 13.4 MJ/kg for Hydrolox, there is over 10 million times more energy available when using nuclear energy. However, the use of pure Uranium fuel is almost unheard of, and common nuclear power reactors use a small fraction, say 3.5%, of Uranium-235 in a non-fissionable binder material. For 3.5% Uranium fuel percentage, the energy density decreases to 3,456,000 MJ/kg.[32] Even in this dilute form, nuclear fissions offers 260,000 times higher energy density than the Hydrolox reaction.[33]

Nuclear Thermal Propulsion Engines

The high energy density means nuclear energy has the potential to provide significantly improved propulsion performance compared to chemical engines. However, most of the available energy cannot be harnessed at this time, as this would yield operating temperatures well above the melting point of all currently known materials. Temperature limitations mean nuclear thermal engines currently have only incremental performance increases for thrust and specific impulses when compared to chemical engines. Advancements in materials science will continually increase thrust and specific impulse into the future.

Nuclear engines can take the form of rockets (closed inlet) or air-breathing (open inlet) systems, and in general have significant similarities to the equivalent chemical counterparts. In each case, the consumable combustion fuel required to produce heat in chemical systems is replaced by a nuclear reactor. The higher energy density of nuclear fuel means operational burn times are increased from hours for chemical system to decades for nuclear systems. The substantive immediate improvement of nuclear systems is therefore significantly increased burn times increasing total impulse and range.

Nuclear thermal rockets[34] operate using similar principles to chemical thermal rockets. However, instead of combining two propellants, one oxidizer and one fuel, to burn in a combustion chamber for heat, the heat energy comes directly from a nuclear fission reactor. Therefore, only one propellant type needs to be carried, which is usually hydrogen or some other light element to achieve the highest exhaust velocities and specific impulses.

The single non-combusting propellant flows over, around, or through, a nuclear reactor gaining significant heat from the fission reaction as is does. The heated propellant expands through a nozzle in the same manner as described above for chemical engines. A nuclear thermal rocket design is shown in Figure 14.

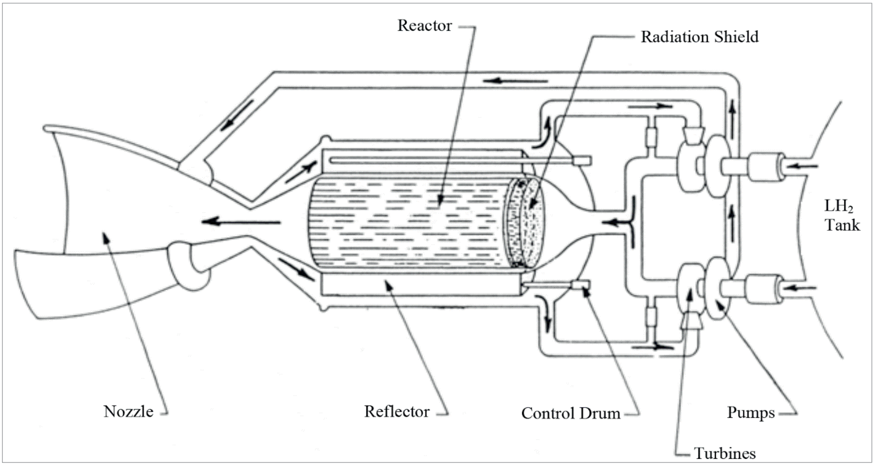

Figure 14. Generic nuclear thermal rocket.[35]

In search of higher combustion temperatures

The reactor core in a nuclear thermal rocket may be a solid core, liquid core, or gaseous core, each one giving higher temperatures than the previous by reducing material limitations. Recall that the higher the temperature of the working propellant, the higher the exhaust velocity and corresponding specific impulse.

1. A **solid core reactor**[36] contains fuel rods, often partially enriched uranium at low fuel percentage levels, a moderator, and control rods to slow or increase the reaction. Temperatures up to 3000K are possible, producing specific impulses around 900 s when using hydrogen propellant. The performance is limited by the melting temperatures of the supporting structural materials and not the energy stored in the nuclear fuel. Improvements in ceramics and high melting point alloys will continue to increase performance.
2. A **liquid core reactor or molten salt reactor**[37] gains higher working temperatures by having the fuel as a salt solution in liquid form. The working propellant bubbles through or passes around the liquid core, which can be at higher temperatures than solid reactors by inducing fluid rotation or other similar techniques, theoretically producing specific impulses up to 1500 s with hydrogen.

3. In a **gaseous core reactor**[38], the fissionable fuel forms part of a gas mixture such as uranium tetrafluoride. Rapid circulation techniques contain the hot gas in a central pocket separated from the physical walls by the working propellant flow. The working propellant absorbs heat from the hot fissionable gas as it passes around the gas core, in theory reaching temperatures over 10,000K. At these temperatures the primary heat transfer method moves from conduction to radiation. Hydrogen is opaque to most thermal radiation wavelengths, so the propellant must be seeded with heavier particles such as tungsten. This permits high propellant temperatures but increases exhaust mass, which decreases specific impulse compared to pure hydrogen. Estimated specific impulses are up to 5000 s.

The configuration of the above gaseous core reactor is **open cycle**[39], meaning both the working propellant and fissionable gas are expelled through the nozzle. This eliminates the need for a high temperature storage vessel for the fission fuel maximizing operational temperatures. However, if the fuel does not completely fission in a single pass through the system then the exhaust may contain radioactive particles.

A **closed cycle**[40] gaseous core reactor eliminates expulsion of radioactive exhaust products by confining the fissionable gas mixture in a closed loop with the working propellant running in a parallel open loop. The requirement of a physical separator between the fissionable gas and the working propellant reverts to operational temperature limits from material properties, decreasing propulsion performance. The difference between open and closed loop cycles is illustrated in Figure 15 and Figure 16.

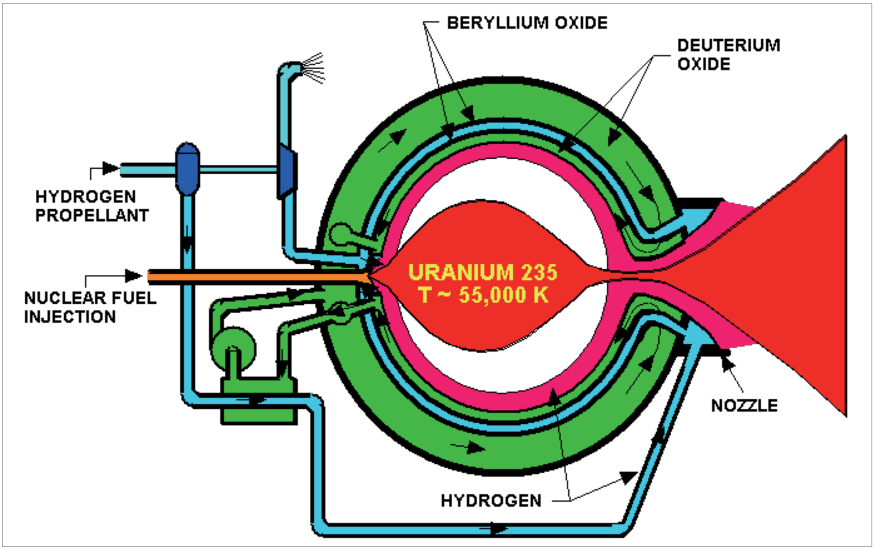

Figure 15. Open cycle nuclear reactor.[41]

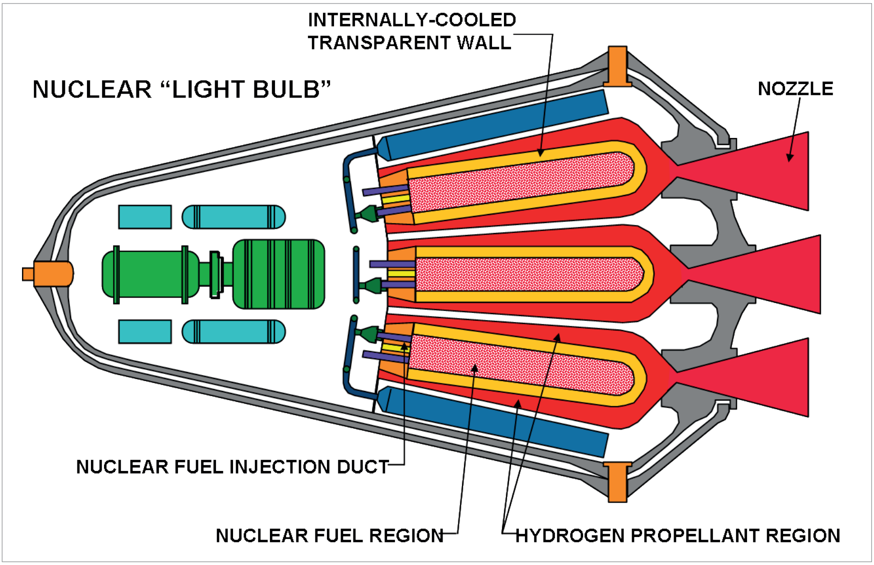

Figure 16. Closed cycle gaseous core nuclear reactor.[42]

Nuclear thermal rockets provide increased performance over chemical thermal rockets, but the main benefit of the high energy density of nuclear fuel permitting longer burn times and range is negated by having to carry the working propellant on-board. Air-breathing nuclear thermal propulsion requires only the ambient air as propellant, significantly extending burn times and range over both air-breathing chemical engines and nuclear thermal rockets.

Air-breathing nuclear turbine engines[43] are similar in principle to air-breathing chemical engines. However, instead of using oxygen in the air to combust with on-board hydrocarbon fuel to release chemical potential energy, a nuclear reactor heats an inert working fluid constrained in a closed loop, such as helium, that heats the air flowing through the engine by heat exchange. Figure 17 shows the general layout of an air-breathing nuclear jet engine that includes a compressor-turbine system to enable operation from stationary conditions.

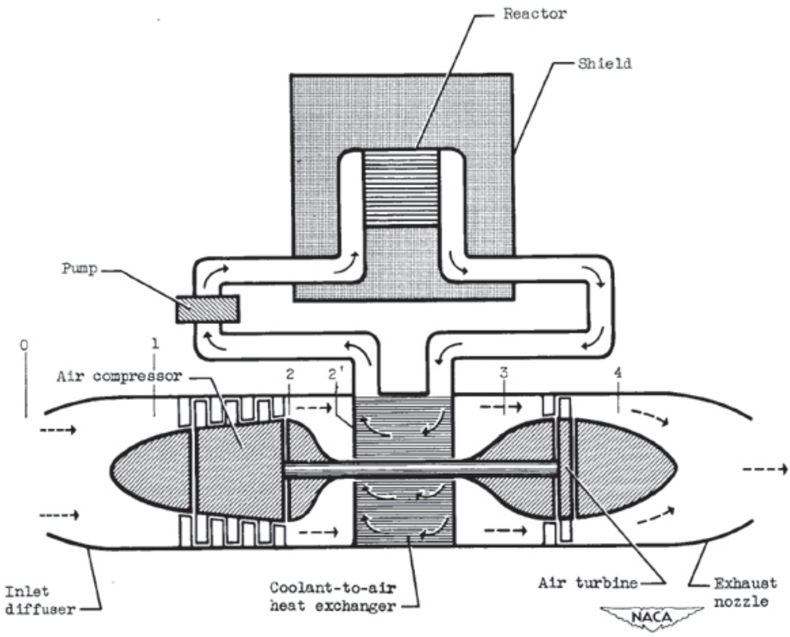

Figure 1. - Schematic diagram of a liquid-metal nuclear powered turbojet engine.

Figure 17. Generic air-breathing nuclear jet engine.[44]

A nuclear fuel rod with diameter 1.4 cm and 1.22 m length provides an equivalent energy source to 189,000 litres of kerosene. Working fluid temperatures are around 1000 K to 1200 K, providing 8300 kW-hr/cm^3 when designed for 10,000 hours continuous operation.[45]

In search of faster flight speeds

A **nuclear ramjet**[46] differs from a nuclear turbine engine in the same way a chemical ramjet differs from a chemical turbine engine. The compressor is removed to prevent the blades from being damaged from high-speed air stagnation on the surface. Then, as for nuclear turbine engines, instead of combusting oxygen in the air with on-board hydrocarbon fuel, a nuclear reactor with closed loop working fluid and a heat exchanger are used to heat the air flowing through the engine. A generic nuclear ramjet is shown in Figure 18.

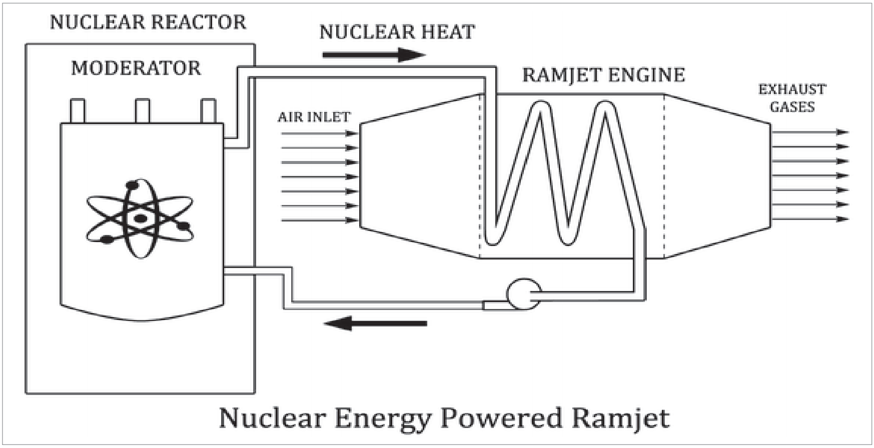

Figure 18. Generic nuclear ramjet configuration.[47]

Alternatively, to reduce system size and frontal profile, a compact reactor may be installed directly into the path the air flowing through the system, as shown in Figure 19. This design is better suited to missiles or other high-speed, narrow body air vehicles.

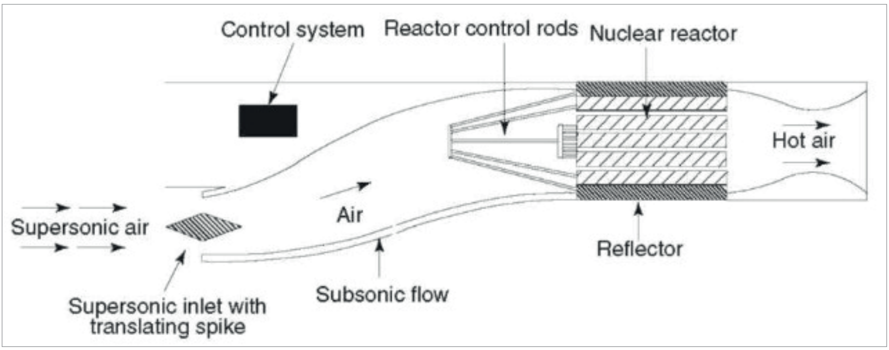

Figure 19. Compact nuclear ramjet configuration.[48]

A 600 MW reactor in a nuclear ramjet, such as that proposed for Project Pluto, could heat the air flowing through the engine up to a temperature of 1400 K, providing sufficient propulsive force to fly a five ton payload at an altitude of 300 m at speeds up to Mach 3 for decades at a time.[49]

Increasing to hypersonic flight speeds (ie above Mach 5) requires the inlet air passing through the engine to remain at supersonic speeds to prevent damage from high temperatures caused by stagnation of the inflowing air. Unlike chemical scramjets, there is no combustion process to introduce supersonic combustion instabilities for hypersonic nuclear engines. However, supersonic heat exchange is not trivial, and the air flow path through and around the reactor would need to be highly controlled to prevent stagnation at any point in the engine or on the air vehicle.

Of course, the name scramjet involves the term 'combustion', so nuclear scramjet does not make much sense. Regardless, there is limited literature currently publically available for hypersonic nuclear thermal engines. In theory, nuclear ramjets flying at speeds from Mach 2 to Mach 4 can follow low altitude powered trajectories below radar detection for decades at a time. These effectively indefinite stealthy trajectories means hypersonic speeds are not required, and challenges related to air stagnation increasing vehicle temperatures above material capabilities do not need to be immediately addressed.

Alternative Design Options for Nuclear Engines

Nuclear thermal engines are the current focus for nuclear propulsion development efforts due to the similarities to chemical propulsion requiring only incremental technology improvements to be feasible. Alongside nuclear thermal propulsion development is the investigation of a number of other alternate nuclear propulsion methods. Significant engineering challenges or environmental considerations have prevented significant development of these alternate engine designs. For example:

1. **Nuclear Pulse Propulsion**[50] – a series of controlled nuclear explosions are detonated behind a vehicle with a strong reinforced pusher plate. The vehicle rides the shockwave of the detonations, pushing it along like a surfer on a wave. Nuclear fall-out from

the detonations prevents use in the atmosphere, but nuclear pulse propulsion has been considered for deep-space missions.

2. **Fission Fragment Propulsion**[51] – To remove the working fluid requirement and efficiency loss in the heat exchanger, using the fission fragments directly as propellant has been explored. Nanofibers or thin layers of fissionable material become superheated during fission events and the fragments boil off the surface. The extreme heat ionizes the fragments, so they can then be funnelled into an exhaust using strong magnetic fields. By using magnetic fields, the superheated fragments to not come into physical contact with the engine walls permitting extreme exhaust temperatures and specific impulses.

A Comparison of Nuclear and Chemical Propulsion Designs

The key differences between chemical and nuclear engines are summarised below.

Specific Impulse: For all variants of nuclear thermal propulsion, the exhaust velocities are higher than the equivalent chemical systems. This is in part due to higher operational temperatures, but primarily from the use of hydrogen gas as a single propellant. Hydrogen is the lightest element and hence attains the highest exhaust velocities for the lowest temperatures. Chemical systems require the use of heavy oxygen as well as hydrogen, so cannot achieve the same exhaust velocities.

Thrust: The higher specific impulses also mean that thrust can also be higher than chemical systems, as long as the same propellant mass flow rate can be maintained. However, using a lighter propellant such as hydrogen may decrease the mass flow rate. For both chemical and nuclear propulsion, high thrust is possible by increasing propulsion system size and expelling more propellant.

Burn Time: For all rockets, regardless of whether the system is nuclear or chemical, all required propellant is carried on-board. Therefore, the total burn time of the system is limited by the amount of propellant carried. For air-breathing chemical systems the ambient air provides the oxidizer with hydrocarbon fuel carried on-board, and the total burn time is limited by hydrocarbon fuel consumption and volume. However, for air-breathing nuclear propulsion systems, the ambient air is the only propellant required, and the nuclear fuel is the only consumable aspect. The reactor fuel source does deplete, but the higher energy density of fissionable material means a small amount of nuclear fuel (a few kilograms) can last for decades.

Radiation: Radiation hazards for standard chemical engines do not exist in significant quantities to warrant consideration. Conversely, the nuclear fission reaction produces a significant amount of radiation in the form of damaging high energy particles. To prevent damage to surrounding avionics, the environment, or biological organisms, sufficient shielding is required to maintain ambient radiation levels below acceptable levels. Using current technologies, it is possible to shield the reactor to below required radiation levels, but shielding materials tend to be quite heavy increasing total system mass.

System Mass: Radiation shielding materials are either very dense or very thick to prevent radiation passing through. Although nuclear propulsion systems carry very small fuel masses when compared to equivalent chemical engines, radiation shielding mass may make overall propulsion system mass equal or higher. During the early phases of the nuclear propulsion programs, system mass from shielding was a significant problem. Improvements in materials science to develop lighter materials capable for effectively shielding radiation will permit lower system mass nuclear propulsion systems.

Range: The increased burn times theoretically achievable with nuclear propulsion systems, especially air breathing systems, while maintaining high thrust levels gives high total impulse values. The system may have an extended range if the system mass permits flight. It is feasible that air-breathing nuclear propulsion systems may have ranges that permit them to circumnavigate the Earth numerous times before landing was required.

Trajectory: As thrust is comparable for both chemical and nuclear propulsion systems, possible trajectories and terminal velocity are also similar for both. However, the extended burn times possible with nuclear systems permits longer powered flight trajectories. For example, a nuclear ramjet could fly on a powered trajectory at altitudes below radar range at approximately Mach 3 for years at a time before needing to land.[52] The system would not need to enter an easily trackable or predictable high altitude ballistic trajectory to cover large distances.

Conclusions

Nuclear engines are technologies to exploit the atomic energy available in fissionable materials as a high density heat source to replace hydrocarbon combustion in air-breathing jet engines and thermal rockets.

Nuclear thermal rockets enable propulsion systems to function in the transit from the atmosphere and into space.

Nuclear air-breathing jet engines can propel air vehicles further than is possible with conventional chemical air-breathing and non-air breathing propulsion systems, in theory permitting flight durations on the order of decades.

The use of nuclear reactors brings increased radiation risks and hazards into aerospace operations that must be mitigated for safe operation of nuclear engines.

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Nuclear Engines in Air Power Doctrine

David Burningham

Introduction

In 1932 the then UK Prime Minister Sir Stanley Baldwin in a speech entitled "A Fear of the Future" stated that "the bombers will always get through"[1], meaning that there was no defence against a massed bombing campaign targeting British cities. The speech advocated the only feasible defence against a massed bombing campaign was to attack first (ie pre-emptive first strike) and with a mass force.

Figure 1. In 1940, the "Lightning War" began with waves of Luftwaffe bombers flying over England to strike London.[2]

In the evolution of aerial warfare systems, there have been many claims about weapons that would always succeed because they were purposely designed to exploit a new advantage over the opposing protection/defence systems. Since the first development of the Second World War German V-2 ballistic rocket, technological advantages in stealth, precision guided weapons, decoys, long-range, and hypersonic speed have all been, or are still being used, to gain an advantage over an enemy's deployed capabilities. To this end, air forces around the world have developed doctrine to fight and win an air war based on the principles of air warfare and not on the technologies of the day.

> "*Throughout its existence, airpower has been continuously reacting to change; either absorbing it or coming to terms with its aftermath.*"[3]

The continual development of new technologies allows nations to revisit old ideas. The SSC-X-9 Skyfall is a Nuclear Powered Missile (NPM) that was first announced publicly by Russia's President Putin in his 2018 State of the Nation address to the Russian Federal Assembly.[4] Putin described the missile as one of a new class of 'invulnerable' Russian superweapons.

Doctrine provides a useful lens for viewing and analysing the significance of technological disruptions to the employment of air and space power. By looking at the essential core air power roles and applying those roles to defend against a NPM, we begin to understand if there exists reliable counter measures that can be employed with the current philosophical thinking. Where the current understanding of air power is assessed to be challenged by a threat from a NPM, new roles may need to be considered.

Aim

This paper will look at the implications to air warfare in defending against a threat from a NPM attack. This will be analysed through the lens of the RAAF doctrinal core air power roles. The core air power roles considered in this paper are: Control of the Air (COA), Strike, Air mobility, and Intelligence, Surveillance and Reconnaissance (ISR).

Nuclear Powered Missile – An Air Power Disruptor?

Using an on-board nuclear reactor to propel a missile provides the NPM with almost unlimited endurance and unlimited range, providing the engine and missile are functioning nominally. This endo-atmospheric missile is essentially an advanced cruise missile that can be launched and loiter anywhere on the globe for indefinite periods. The Russian announcement and the missile appear to be an attempt to destabilise the nuclear balance of power that has existed since the New Strategic Arms Reduction Treaty[5] (New START) came into agreement between Russia and the United States of America. In essence, the SSC-X-9 Skyfall may well be viewed as Russia's opening salvo of what could become a new technology-driven arms race.

Figure 2. Russia is developing a nuclear-powered cruise missile that has been designated the SCC-X-9 Skyfall.[6]

Air forces around the world may need to revise how air warfare, and particularly air defence, is conducted against this new potential threat. Current anti-missile and missile defence systems may be overwhelmed with multiple targets arriving concurrently from many directions. Additionally, the NPM now provides the potential to strike with singular or potentially swarms of missiles including the ability to remain airborne indefinitely in their routing to approach a defended target.

How does Australia and other nations counter this threat, what are the implications to a missile with a nuclear engine crashing (or being shot down) near a populated area? How will the nuclear technology be managed if Russia chooses to export the weapon to other nations? What are the implications to swarms of NPMs clouding the airspace threatening air defence systems or denying airspace for civil and military aircraft? Is this a new weapon that has the potential to realise the prediction made by Sir Stanley Baldwin or are we just in another cycle of countering a threat to the status quo? Are the current air power roles within RAAF doctrine still relevant and does the narrative still meets its intent?

Australian Air Power Doctrine

The application of military air power in the furthering of government interests is the reason for the Royal Australian Air Force to exist. Air Force doctrine communicates the sanctioned war-fighting principles that guarantee air power is versatile, flexible and efficient in a diverse range of military activities. In essence, airpower doctrine details the fundamental principles by which military forces guide their actions to achieve desired objectives.

Air Force doctrine is not policy. Rather, it is a description of Air Force knowledge in the conduct of air operations ranging from the philosophical through to applying that knowledge procedurally. Air Force doctrine is authoritative but not prescriptive; it requires judgment in its application and is the foundation for innovation in changing and challenging circumstances. Sound doctrine is based on research and analysis, it can sometimes be a trap to expect that the latest thought does not necessarily represent new ideas or the best path ahead. While the 'Principles of War'[7] are enduring, sound doctrine results from an innovative and progressive application of these principles.

Military lessons gained from history, theory, technology, experimentation, cultural exchanges, policy, and broad and diverse estimates of the future operating environments all influence Air Force doctrine. Because culture and wider society influence the efficacy of doctrine, it should reflect the norms, and accepted cultural and social standards. These inputs, some of which are contradictory in nature, will profoundly affect the operating principles adopted by any military organisation.

Understanding their nature and effect is essential to developing doctrine and anticipating potential change in a timely manner. The term 'doctrine system' is used to acknowledge that Air Force doctrine must be established through analysing inputs, influences and operating intent. To achieve the desired outputs from the analysis, an organisation is required to be dedicated to doctrine development and education. While 'doctrine' may be expressed simply as fundamental principles that guide the planning and execution of actions, 'doctrine system' refers to all the components necessary to realise an organisation's doctrine.

Control of the Air

> "The ability to conduct operations in the air, land and maritime domains without effective interference from adversary air power and air defence capabilities." [8]

Almost all operations whether single service or joint in nature require some level of air control to enable the safe and assured conduct of other national activities, free from the threat of attack, with a necessary freedom of manoeuvre. Therefore, COA provides friendly commanders with the flexibility to exploit the air environment to achieve desired objectives. Controlling the air does not guarantee success and will not win wars alone. However, "it is the primary prerequisite for the success of all operations to achieve campaign objectives."[9]

As missile technology has advanced in capability and range, the ability to defend and control[10] sovereign airspace has become increasingly important. With the ability of NPMs to loiter indefinitely anywhere on the globe they may compromise a nation's early warning capacity and, by extension, reduce their ability to effectively use anti-air defences, the rise of these capabilities will seek to exploit any coverage gaps previously unable to be used. With a reduced ability to detect and neutralise an inbound threat, nation states becomes vulnerable, and in turn more unpredictable.

So how will COA be contested in this environment, is this just another missile threat? A number of countries around the world already have an integrated missile defence system, able to detect, track and intercept incoming ballistic missiles thereby destroying an attacking missile on a straight trajectory. However, In the event of conflict, competing states could find NPMs attacking from previously unusable (and hence unprotected) trajectories. How then is the airspace controlled when potential weapons of mass destruction can loiter in close proximity to a nation's border poised to be used at any time without warning? Can air platforms play a part in targeting NPMs in an integrated system and so provide another level of defence? Could this type of international behaviour be used to shape non-aligned nations with the same coercive behaviour that parking a Naval asset off a protagonist's coast was used by western nations in the past (ie. gunboat diplomacy).

In a paper by Dario Leone it was reported that Lockheed Martin Skunk Works, the Missile Defence Agency and the US Air Force successfully data connected an F-35, a U-2, and a ground station in a demonstration of multi-domain operations including the secure distribution of sensitive information across multiple platforms.[11] In this demonstration called Project RIOT, an F-35 detected a long-range missile launch with its on-board sensors and shared that information through the U-2 to the air defence commander on the ground, informing the commander's decision to target the threat, in a clear demonstration of the ability to use 'any sensor, any shooter' in a combat network. With the current levels of data exchange, decision timelines are drastically reduced allowing decisions to be made in seconds rather than minutes. This layered approach to airspace management allows all aircraft to be an integrated part of an air defence system.

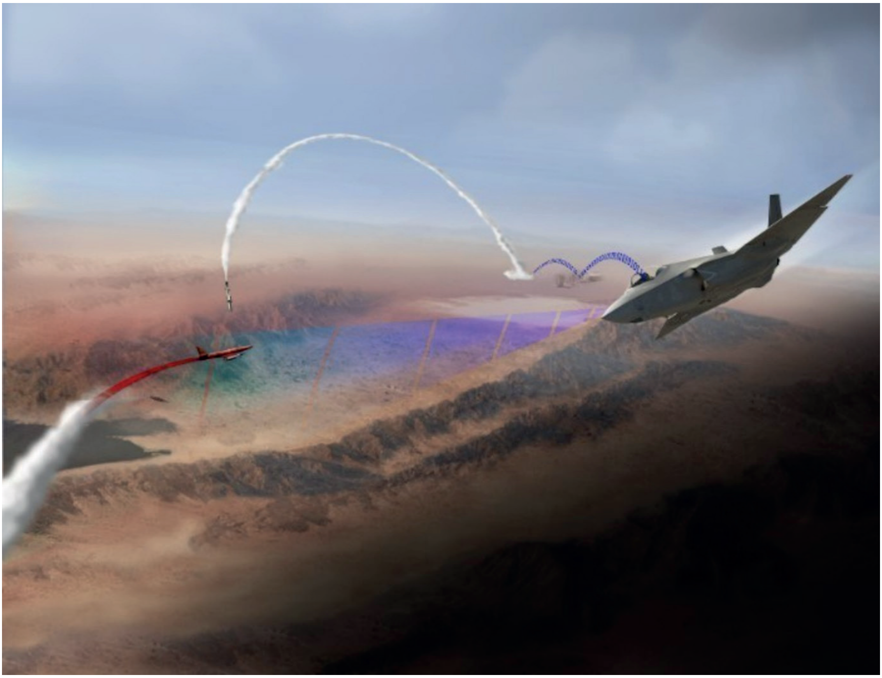

Figure 3. The ISR sensors on the F-35 can be integrated into a networked fire control system for effects delivered by other platforms.[12]

What this means for COA is that we are seeing the beginnings of an aircraft counter to a cruise missile attack. With the ability to target incoming NPMs approaching a border by an advanced detection and targeting system, NPMs will become less of a threat to the populous. It should be noted however that the NPM still carry nuclear material, which will not be shielded effectively. Any debris from a destroyed (or failed) nuclear missile will be highly radioactive significantly contaminating the ground where it falls, as demonstrated by the 2019 Russian nuclear accident in northern Russia.[13] It therefore behoves the wider international community in developing and enforcing effective rules around the use of nuclear power plant in weapons. Additionally the recovery of remnants from this type of weapon would be fraught with radioactive hazards, not only to the personnel required to clear up the debris but also to the environment for a period that may extend beyond the period of operations.

The current direction for modern militaries to be networked and integrated allow nations (using aircraft, rather than traditional air defence sensors) to mitigate some of the advantages of this extremely long range threat, in order to 'fill the gaps' in an established system. There are still lessons to be learnt for updating air power doctrine practitioners on the ways that control of the air should be updated for the employment of modern piloted and remotely piloted aircraft to defend against long range first strike missiles as part of an integrated networked missile defence system.

Strike

> "The ability to attack with the intention of damaging, neutralising or destroying a target."[14]

From the lens of the deployment of an NPM, an airborne missile is very difficult to recover safely, this is in part due to shielding limitations as discussed in other papers in this title. An inherent assumption is that once launched, a NPM will inflict nuclear radiation damage of some sort, whether at the weapon launch site on failure, during an abort in flight or at the designated target; additionally the nominal functioning of a nuclear engine will generate nuclear contaminants from the jet exhaust. Options for a water recovery, or splash still carries many risks most notably the environmental contamination and/or recovery personnel.

The decision to launch should be calculated against to a recognised threat, this is a first strike weapon that has a potential 11th hour delay, but is non-returnable. Allowing these weapons to orbit the earth on an endo-atmospheric trajectory indefinitely based on a limited threat is a reckless and costly concept of operations. However, this technology is not new and parallels can be drawn between the danger of this technology and the ballistic missile arms race following the Second World War.[15] This has the potential for the globe to end up in the same spiral that has caused the limited use of near space due to debris orbiting the earth.

Potential concepts for a NPM flying trans-global distances is for multiple airframes to approach an objective from the same direction in order to overwhelm or saturate defences, or from different azimuths to deliver a warhead as a precision strike. Air Forces do have a role to play in stopping a NPM. However, defences against swarms require an integrated network of sensors that can detect low flying and possibly low observable threats approaching target areas from multiple trajectories, secure communication links that can quickly pass data to decision makers with appropriate training and expertise in operating advanced integrated systems and a multitude of offensive systems to mitigate the threat.

The NPM is a strategic weapon that could has the potential to be used as a weapon of mass destruction that, once fired, cannot be safely recovered. This is a first strike weapon designed to exploit a weak spot in the missile defence system. Air Forces, along with Navy form the first line of defence and have a major role to play in the advanced detection and interception of incoming threats. With advanced platforms integrated into a wider network of defensive systems, the threat of NPM may be neutralised. However this will require a far more automated system than previously fielded and highly technical personnel, while, also understanding the interdependencies that exist across all assets in a joint service environment. Air Force is no longer defined by how its capable its platforms are, moreover it is how these assets will be utilised in a multi-domain, joint service environment.

Air Mobility

> "Air Mobility is the ability to move personnel, material or forces using airborne platforms."[16]

Modern military forces rely on air mobility in order to provide manoeuvre capabilities for strategic effect and operational advantage over an enemy. This includes the ability to conduct humanitarian assistance or to deploy airborne troops. However, air mobility can also include the movement of civilian air traffic for passenger travel or logistics support to a nation.

Whether a NPM is launched as a single missile or a salvo, the use of airspace in which the NPM travels will pose a risk to other air traffic. Anti-Access/Area Denial (A2/AD) is a concept used to deny an adversary freedom of movement in a defined battlespace. A NPM passing through a piece of airspace has the potential to deny that space, particularly as it's unpredictable in nature and trailing radioactive particles in its wake. While the location can be tracked and treated like other aircraft, the risk analysis in using the same airspace as the circulating NPMs may act to deny that to a user. This has particular impact on civil aircraft, which may not have the use of advanced detection and identification devices.

Certainly, the possibility for traffic congestion is increased and the use of trans-global cargo delivery and recovery will be adversely affected. For countries that are crucially dependent on air traffic for infrastructure support, denial of airspace or air routes may be another outcome for NPM as a more overt form of 'gunboat diplomacy'. Certainly, there is no easy answer to the problem of denied airspace. Dispersing forces will reduce losses and increased detection and tracking will allow some use of contested airspace.

As heavy lift aircraft and tankers are normally deployed into benign operating areas for their self-protection, they will normally be based in the rear areas of a joint area of operations. This will create an increased reliance on air-to-air refuelling in providing the necessary air bridge. The use of any contested airspace will become limited to predicting (or eliminating) the threat of a NPMs likely flight route and asserting control of the air.

Intelligence, Surveillance & Reconnaissance

> "ISR synchronises and integrates the planning and operations of centres, assets, and processing exploitation and dissemination systems in direct support of current and future operations."[17]

In doctrine, ISR is understood to be an air power role, an air power mission, a process, a capability and an enterprise subject to the context, which it is viewed. As an air power role, ISR enables battlespace awareness, information superiority and decision superiority, and thus is critical to the successful conduct of ADF operations.[18] ISR systems comprises of various platform, sensor and exploitation networks that support the RAAF ISR enterprise. This enterprise comprises three system groups: environmental; information communications technology (ICT) and cognitive. Environmental systems are those systems that reside in or operate in a particular environment (eg. air) and include things such as unmanned aerial systems and space-borne systems.[19]

The goal of ISR activities are to provide accurate, relevant, and timely intelligence (and data) to decision-makers and operational commanders. This allows strategic decision-makers to determine the necessity of certain operations and for operational commanders, it provides the intelligence and situational awareness necessary to successfully plan and conduct those operations. The combined drone and cruise missile attack on the Aramco refinery in Saudi Arabia that took place on 14 September 2019[20] was a stark demonstration as to the limitations of defences against this type of attack without continued vigilance and intelligence support.

When it comes to defending infrastructure, there is no one-size fits all approach to design countermeasures and air defence systems. A key success in conflict is the effective use of information as a vital weapon of war. As weapons have become more precise, engagement criteria more stringent and targets more difficult to find, fix and track, ISR has become increasingly critical to the war fighter. Precise weapons require accurate intelligence and as such, ISR is of paramount importance to air power because it provides the backbone for the successful application of air power directly enabling the air campaign planning process.

Through this new technology of NPM, ISR is a critical enabler in enabling each phase of the dynamic targeting process, Find, Fix, Track, Target, Engage and Assess (F2T2EA). While this is important during conflict, it also has a critical role in the intelligence preparation of the battlespace, such as consistent monitoring of NPM launches or tracking the flight path of airborne NPMs. This becomes increasingly difficult when the weapon can fly indefinitely, the target area is essentially the globe and because of its ability to manoeuvre cannot be predicted (as ballistic trajectories can be). As discussed above, the most direct effect on current RAAF doctrine of this new capability will be in the ISR domain, significantly testing currently fielded systems.

A requirement for Networked, Multi-Domain Operations Doctrine

Interception of cruise missiles presents its own challenges, in strategic terms it is often the only option, especially during the period preceding an outbreak of full-scale hostilities. The argument could be made, that in launching an irrecoverable weapon, the aggressor is signalling the start of hostilities. As NPMs present an escalation before a first strike weapon designed to disrupt air defence infrastructure, their use is most likely in the opening round of a conflict.

It should also be noted that in the A2/AD environment, airborne C2 and ISR collection could be very difficult without significant risks to the high value platforms. Thus, intelligence preparation of the battlespace, persistent situational awareness and decision-making processes need to be managed appropriately to reduce the risks of asset loss.

The effectiveness of an ISR capability is not determined simply as the sum of the capabilities of individual assets; it is also the outcome of the way in which these capabilities interact to create actionable information and intelligence. This interaction should occur on a theatre-level scale, drawing together geographically dispersed ISR capabilities. In mitigating against a NPM threat, ISR provides not only advanced detection but also enables important communication into an integrated defence system.

To implement either deterrent or direct counterforce strategies in order to defeat an opposing NPM attack requires significant ISR/targeting and strike capabilities from multiple combat assets that are not necessarily owned or operated by Air Force. This strategy will require an aggressive engagement and surveillance zone to allow for a layered defence systems and clear any collateral radioactive contamination from sovereign shores. Then plans will need to be laid for counter force attacks against enemy air bases, missile launchers and supply depots before take-off and launch, thus reducing the ability of a state actor to connect swarms against a target. Long-range detection of threats is valuable because the resultant warning allows for the preparation of an effective defence.

In practice, any model for countering a NPM must exploit multi-layered sensor and interconnected weapon response systems to assure a timely and high probability detection from across a nearly global operating area. Ideally, NPM can be detected, tracked and engaged from launch, and if this fails, the small NPM must itself be detected, tracked and engaged a far harder proposition. The air-sea gap is valuable in this respect, as it provides a de-facto free-fire zone for weapons systems tasked with NPM intercepts, and the distances involved provide for repeat engagement opportunities.[21]

Conclusion

NPM missiles present a niche challenge to sovereign air defences for a variety of reasons. In comparison to first-generation German V-2 rockets that launched into Britain during the Second World War, modern missiles fly at one-tenth the altitude and have radar cross-sections one hundred times smaller.[22] As with conventional weapons systems, they have the potential to arrive in large numbers and overwhelm defences, even if detected in time to enable engagement, the complicating factor with NPMs in particular is the potential for previously unusable attack trajectories, and the radioactive nature of the engine.

Whilst conventional anti-missile defences may continue to be viable, NPM presents a disruptive game-changer to air power thinking. If anti-missile defences (eg missile or aircraft) can find a NPM, they may be able to successfully engage. However, the NPMs ability to fly extremely long-endurance and long-missions will disrupt air defence concepts derived from current air power doctrine. NPM can fly or loiter until air defences are vulnerable, depleted or deployed and manoeuvre into gaps in the coverage of networked air defence systems.

Reliance on land based anti-missile systems alone for on-site defence of target areas is a popular but relatively ineffective strategy, as high performance anti-missiles need expensive high power-aperture radars. Any defence against this technology will need to be multi-layered and integrated with a workforce that understands operating in the 21st century in a digital world. While technology has changed significantly, and the way that the RAAF interacts with technology has changed. However, the current doctrine principles of Australian air power remain valid today as much as they did when they were first derived after experiences gained in the First World War.

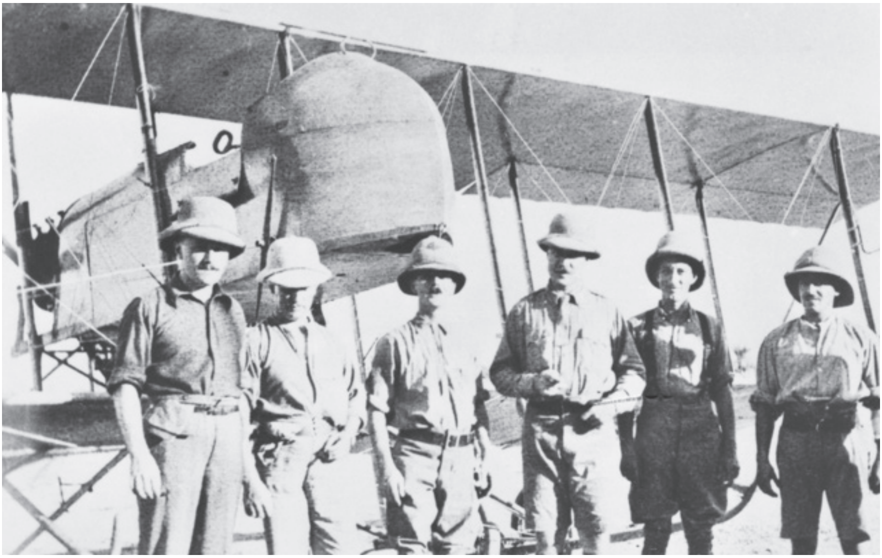

Figure 4. The fundamental principles of Australian air power doctrine were first derived from experiences gained in the First World War.[23]

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Nuclear-Engine Air Power Case Study: Russian SSC-X-9 Skyfall

Michael Spencer

Russia successfully launched its latest nuclear-powered missile at the Central training ground. During its flight, the nuclear-powered engine reached its design capacity and provided the necessary propulsion. Now that the missile launch and ground tests were successful, we can begin developing a completely new type of weapon, a strategic nuclear weapons system with a nuclear-powered missile. You can see [in the video] how the missile bypasses interceptors. As the range is unlimited, the missile can manoeuvre for as long as necessary.

– Russian President V Putin (2018)[1]

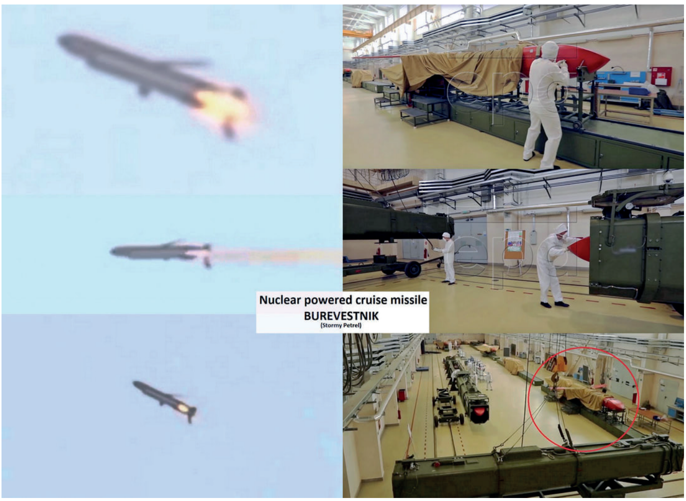


Figure 1. Russian flight testing of the SSC-X-9 Skyfall missile.[2]

Introduction

'Storm Petrels' are one of the families of tube-nosed seabirds, similar to the albatross, all of whom are commonly referred to collectively as 'Petrels'. During the nonbreeding season, these birds roam the open ocean and can travel very long distances over water. Albatrosses that nest on small Antarctic islands can circle the globe during their migrations; one such bird, banded as a chick at Kerguelen Island in the southern Indian Ocean and recovered in Chile, travelling at least 13,000 kilometres and, perhaps, as far as 18,000 kilometres.[3]

Superstitious sailors gave the Stormy Petrels nicknames such as 'water-witches', 'satanites', and 'oiseau du diable' (ie 'bird of the devil'). Sailors believed that its appearance prognosticated stormy weather.[4] 'Storm Petrel' is the English-language name that was given to Russia's new 9M730 Burevestnik long-range strike missile after a vote by the Russian public in response to a 'name that weapon' survey organised by the Russian military.[5] NATO has named the missile as the SSC-X-9 Skyfall[6] (the US intelligence community calls the missile the KY30).

Whilst the US and Soviet Union both investigated nuclear propulsion systems in the 1950s and 1960s, neither country was able to develop an acceptable design for operational use. Russia has now purportedly tested and accepted the SSC-X-9 Skyfall as the first operationalised nuclear engine surface-to-surface guided missile.

Storm Petrel was first announced publicly by Russia's President Putin in his 2018 State of the Nation address to the Kremlin. He described the missile as one of a new class of 'invulnerable' Russian superweapons using an on-board nuclear-powered engine to propel the missile to hypersonic speeds with unlimited endurance and unlimited range.

Strategic innovation

Storm Petrel was first announced publicly by Russia's President Putin in his 2018 State of the Nation address to the Russian Federal Assembly.[7] He described the missile as one of a new class of 'invulnerable' Russian superweapons that is a nuclear-powered and nuclear-armed cruise missile with effectively unlimited range.

When two super powers consider they have achieved parity in their weapons technologies in order to support their national objective, they will endeavour to seek competitive advantage by being the first to develop innovative and niche capabilities. The SSC-X-9 Skyfall can be considered a potentially new application for an old design for a nuclear engine, where the competitive advantage is gained by Russia having the ability to disregard global norms and rules for the safe and appropriate uses of nuclear materials. Particularly with the deliberate release of nuclear reactors and nuclear fission waste products into the environment.

The nuclear-engine is based on a nuclear reactor that heats readily available atmosphere into a high-speed jet exhaust. The combination of a nuclear reactor and using air as a propellant, can potentially achieve potentially unlimited endurance and unlimited range, allowing a missile to fly for much longer and further than conventional missiles. This would allow a nuclear powered missile to fly the long way around forward deployed air defences, skirt around entire continents or fly circuits around the globe until commanded to engage its target.

Nuclear weapons of mass destruction

Categorising Weapons of Mass Destruction

The criteria used in the UN Treaty on the Prohibition of Nuclear Weapons[8] to define a nuclear weapon refers to the made-for-purpose nuclear warheads or nuclear explosive devices; there is no reference to nuclear fuel or nuclear-powered engines. Although the nuclear material in the nuclear engine and jet exhaust will cause ionising radiation and nuclear contamination along the flight route and at the point of impact, it is not used as criteria for categorising a conventional weapon as a nuclear weapon of mass destruction (WMD). It is the purpose-designed nuclear warhead that categorises a weapon as a nuclear WMD.

'Nuclear-Powered' is Not Necessarily a Qualification for Weapon of Mass Destruction

The SSC-X-9 Skyfall could potentially be configured with either a conventional high-explosive or a nuclear warhead. As described above, it is the warhead that determines the classification of a weapon as nuclear WMD when considering the constraints of international treaties. The US DoD has defined 'weapons of mass destruction' as *"chemical, biological, radiological, or nuclear weapons capable of a high order of destruction or causing mass casualties, and excluding the means of transporting or propelling the weapon where such means is a separable and divisible part from the weapon. Also called WMD. (JP 3-40)."*[9] Since the nuclear reactor is a discrete subsystem of the SSC-X-9 Skyfall missile system, and only intended for propelling the missile, then it alone is not the determinant for qualifying the missile as a WMD; it is the status of the missile's warhead that determines its WMD status.

Nuclear energy effects and fission products

Uranium-235 as a Thermal Energy Source

Natural uranium consists of about 99.3% Uranium-238 and 0.70% Uranium-235 (U-235). The nuclei of uranium 235 and 238 are the heaviest metals present in nature with a melting point of 1132°C. They can only be formed in the explosive chemical reactions occurring in the supernovae of heavy stars. The half-life of Uranium-238 is about 4.5 billion years, while U-235 has a half-life of about 700 million years.[10]

U-235 is useful as a natural energy source because under certain conditions the nuclei of U-235 individual atoms can spontaneously split into smaller atoms. The sum of the masses of the smaller atoms that result from the spontaneous splitting is less than the mass of the original nucleus; the difference in the total mass is released during fission as energy. U-235 is therefore described as a 'fissile' because its nucleus can spontaneously split and release energy in the forms of gamma radiation and heat in a process called 'nuclear fission'.[11]

This naturally generated heat can be captured to make mechanical systems perform a function, such as power generation and jet propulsion. However, all isotopes of uranium are naturally unstable and radioactive; the introduction of uranium introduces new risks and hazards into any system design.

Using a Nuclear Fission Reactor to Heat/Expand Air for Jet Propulsion

Nuclear energy generation is dependent on nuclear fission as described above, Uranium-235 is the only fissionable uranium radioisotope that is suitable for use in generating nuclear energy.

Fission in radioactive material such as U-235 may occur spontaneously but is usually caused by the nucleus of an atom becoming an unstable heavy nucleus after capturing and absorbing a free fast neutron. During fission the heavy nucleus splits into two nearly equal parts as separated nuclei for at least two lighter atomic elements. In addition to heat energy, this fission reaction may also release gamma radiation and more fast neutrons.[12] The new fast neutrons then go on to strike the whole nuclei of other whole U-235 atoms, causing their nuclei to similarly split, releasing neutrons and heat energy, and so on with splitting other atoms in a cascading effect.

If the neutrons are not deliberately slowed down, then the high-speed neutrons may fail to collide and interact with atomic nuclei and the nuclear chain reaction may not be sustained. A nuclear chain reaction can only be sustained with the use of a moderator - a material that can slow down a neutron without absorbing it. Slowed neutrons are more likely to react with Uranium-235 to sustain the fission process and generate a steady supply of thermal energy needed for the engine to function and heat the subsonic airflow.

The nuclear energy is used to heat the air passing through the reactor. In using air as a propellant, there is no need to carry an on-board storage of propellant. Since air is readily available in a useful quantity, provided the vehicle is flying within an appropriate range of altitudes with the appropriate air density. Thus, the nuclear engine will continue to function for an extremely long time and, in theory, could potentially provide an unlimited range so long as the engine and airframe continue to function correctly.

There are two possible design approaches for employing a nuclear reactor within a propulsion engine.[13] Each design outputs different amounts of radioactive contaminated jet exhaust.

1. **Direct-cycle engine** - the airflow through the propulsion system is used to directly cool the hot nuclear reactor and generate hot exhaust gases for generating thrust.
2. **Indirect-cycle engine** – a liquid-metal coolant is used within a closed reactor system to indirectly transfer heat from the hot reactor rods to the passing airflow in order to generate hot exhaust gases for generating thrust.

Radioactive Waste

It is an unavoidable problem with the nuclear-engine missile that it emits a radioactive 'jet exhaust'. If the reactor in the nuclear engine is unshielded, it can emit dangerous levels of gamma and neutron radiation. As the reactor functions to propel the missile, it will continuously eject radioactive fission fragments into its exhaust.

To make the reactors small, light, and affordable to be designed into a missile airframe, the reactors may not have a normal amount of protective shielding, in order to reduce the weight burden in the design of the missile. A USAF study for potentially using a nuclear engine in Global Hawk estimated that it would also need to add 2700 lbs (ie 1220 kg) of shielding.[14] The released radiation can be a harmful contaminant to the environment, wherever the missile flies and impacts the ground, with residual radioactive effects that endure beyond the missile's mission for the duration of the radioactive material's half-life.

The nuclear fission reactions in the reactors produce 'fission products' that are radioactive waste products and categorised as high- and low-level radioactive waste.[15]

1. **High-level radioactive waste, with shorter half-life**. U-235 atoms in the nuclear fuel rods are split by nuclear fission to generate the thermal energy for the ramjet engine to function. The resultant split atoms, or fission products, are radioactive isotopes of lighter elements such as cesium-137 and strontium-90. These isotopes account for most of the heat and penetrating radiation in high-level radioactive waste. Cesium-137 and strontium-90 each have a half-life of about 30 years.

2. **Low-level radioactive waste, with longer half-life**. Some U-235 atoms capture and absorb free neutrons produced from the nuclear fission, without splitting. These uranium atoms form heavier elements such as plutonium that produce less heat and radiation than the fission products but take longer to decay (eg plutonium has a half-life of 24,000 years).

Whereas building a steel bomb casing can be designed to withstand the initial impact with the ground without breaching, in order to penetrate to reach deep-buried underground targets, a nuclear-engine missile carries a nuclear reactor that cannot be designed to survive a ground impact and prevent radiation spillage as collateral damage. It is likely that if a nuclear reactor could be made safe to withstand a ground impact, the size and weight of the shielding and protective casing would be incompatible with any feasible design for a flying vehicle.

Excluding the intended consequences of deliberately employing nuclear warheads, any accidental collision with the ground or another air vehicle, or impact at the mission objective (ie including jettison, mission abort, or successful missile strike) will release the reactors nuclear fuels at the point of impact as nuclear contaminants released into the environment. Local environmental conditions, such as weather and flowing water, could further spread the nuclear contaminants.

Nuclear propulsion for aircraft has been deemed impractical for these very reasons: the uncontrolled release of radioactive exhaust into the atmosphere and the weight penalty of a safe nuclear engine (ie nuclear reactor, heat exchanger, radiation shielding, protective housing, etc) makes any design for a crewed aircraft not feasible.

The development of a nuclear-engine for air power

During the Cold War the United States and the USSR in the late-1950s, both nuclear super powers separately conducted research programs to investigate prototype designs for nuclear-powered ramjet engines for use in long range strategic strike missiles and their crewed bombers. Both nations were pursuing options for increasing the operating ranges of their strategic air power. Longer effective ranges required more fuel and bigger fuel capacity storage tanks required bigger aircraft: with a focus on atomic energy systems, nuclear engines were viewed as a potential alternative option to designing larger aircraft.

The US developed Project Pluto[16] to investigate a prototype nuclear engine design to keep a missile flying for a long time, manoeuvre extensively to evade defences, loiter until needed, and then strike a distant target with a high level of accuracy. However, none of the prototype nuclear-engine designs for missiles or aircraft were operationalised by the US or USSR. There are a number of technical challenges in designing a nuclear reactor for a ramjet for a long-range supersonic cruise missile, including designing a small and lightweight reactor and the need to minimize radiation leakage from the reactor core.

Variations in Propulsion Engine Designs

Missile propulsion engines are typically designed to generate energy released by exothermic chemical reactions of a propellant and oxidant. The chemical reactions release heat, causing rapid thermodynamic expansion of the gaseous products of combustion. The high-speed expulsion of these gases, in a rearward direction, generates the thrust that propels the missile in a forward direction.

1. A **ramjet engine**, as depicted in Figure 2. Depiction of simple ramjet using air as a propellant., relies on a very high-speed airflow at the air intake for the engine to function. This normally requires the addition of a rocket booster motor to accelerate the vehicle until the airflow has a speed that is adequate make the engine function. The air is a naturally available oxidiser and is directed into the combustion chamber to be combusted with the propellant, carried in on-board storage tanks inside the missile. The combustion of the propellant and oxygen heats up the passing air which then flows through a specially shaped exhaust nozzle to provide forward thrust to the missile, accelerating it to supersonic and hypersonic speeds. If intake airflow is not slowed to subsonic speed, then it will need a much longer engine to capture thrust by the heated air exhaust.

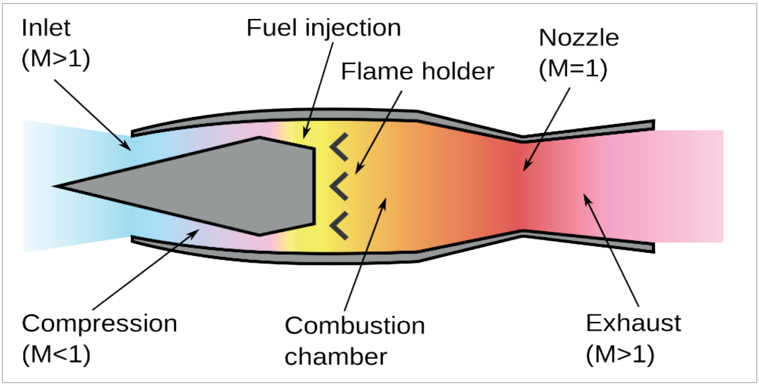


Figure 2. Depiction of simple ramjet using air as a propellant.[17]

2. A **rocket engine**, as depicted in Figure 3. Depiction of rocket engine using liquid propellant. generates thrust by combusting propellant and oxidiser, supplied from on-board storage tanks. The propellant and oxidant are mixed and combusted in the combustion chamber. The combustion products are exhaust through the nozzles, creating a thrust that accelerates the vehicle in the forward direction to supersonic speeds. The propellants are stored in separate tanks in liquid-fuel rockets or as prepared as a fuel-oxidizer mixture in solid rocket motors.

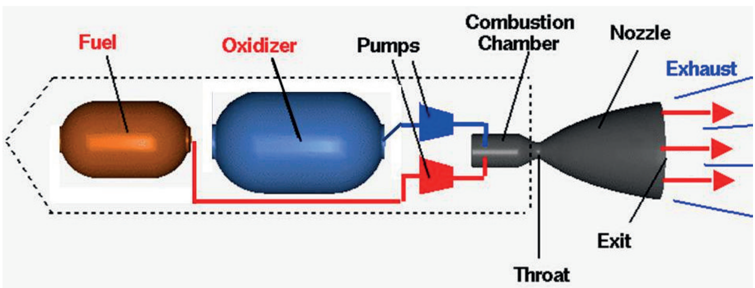


Figure 3. Depiction of rocket engine using liquid propellant.[18]

1. A **Nuclear Thermal Rocket (NTR) engine**, as depicted in Figure 4. Depiction of nuclear thermal engine using stored hydrogen as a propellant., low molecular weight hydrogen is carried by the vehicle for use as the propellant. The hydrogen is heated and not combusted; no oxidiser is needed by the system. The propellant is heated to high temperatures in the nuclear reactor to produce an expanded gaseous airflow that that is ejected through the exhaust nozzle to generate thrust and propel the vehicle forward to supersonic speeds.

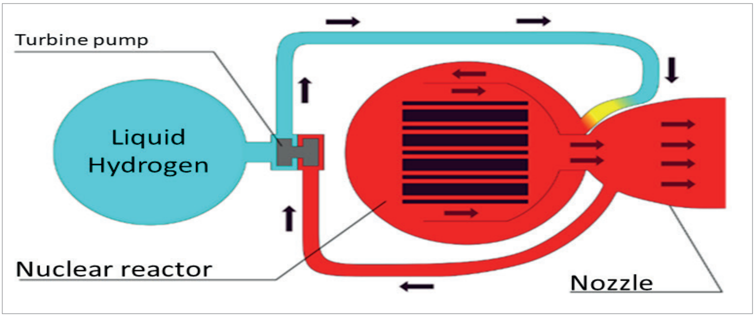


Figure 4. Depiction of nuclear thermal engine using stored hydrogen as a propellant.[19]

2. A **nuclear air-breathing ramjet engine**, as depicted in Figure 5. Depiction of nuclear air-breathing ramjet using air as a propellant., relies on a very high-speed airflow at the air intake for the engine to function. This normally requires the addition of a rocket booster motor to accelerate the vehicle until the airflow has a speed that is adequate make the engine function. This airflow is heated to a very high temperature in the nuclear reactor. However, the air intake be carefully designed to minimise inlet shock waves and reduce the supersonic speed of the airflow to subsonic speeds so that the air can be heated over the reactor core and then accelerated in the jet nozzle to generate the thrust needed to propel the missile forward to supersonic speeds; if the airflow is not decelerated then the air

will not be adequately heated as it passes through the reactor (ie over the hot reactor rods).

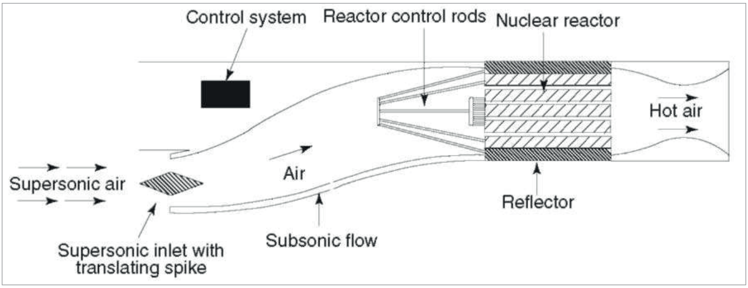


Figure 5. Depiction of nuclear air-breathing ramjet using air as a propellant.[20]

3. A **nuclear-powered turbine**, as depicted in Figure 6. Depiction of a nuclear-powered jet turbine using air as a propellant, could potentially generate enough thrust to propel a missile forward at subsonic and low supersonic air speeds. The axial compressor blades are turned over to draw in the air and start the airflow over the nuclear reactor. The nuclear reactor is used in lieu of a fossil-fuel driven combustion chamber to heat the passing air. The heated air creates a more energetic airflow which drives the turbine on its way to the jet exhaust.

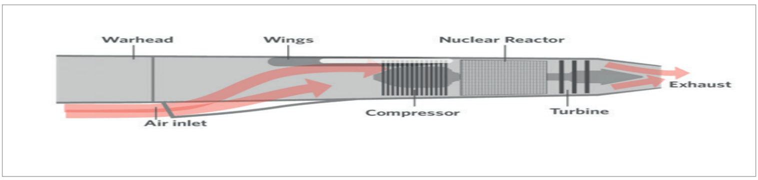


Figure 6. Depiction of a nuclear-powered jet turbine using air as a propellant.[21]

Physical impact of nuclear fission products on missile systems

For many reasons, particularly nuclear safety, nuclear reactors are regarded as having a fundamentally fragile system design. Configuring a small nuclear reactor into an autonomous long-range strategic cruise missile and flying at supersonic to hypersonic speeds in air requires system designers to consider additional types of stresses on the system[22] that are not normally considered with nuclear reactors in fixed infrastructure:

1. **Atomic safety: keeping the reactor cool without airflow in static missile**. Nuclear fuel rods are naturally hot and need cooling for critical reasons of personnel safety and damage prevention. The nuclear-engine is normally designed to use passing airflow, from the normal ramjet operation, to cool the reactor and internal structure. It is assumed that the missile storage canister serves as a launcher mechanism with an external cooling system and protective radiation shield for the installed reactor.

    Note: This also has consequences for the designs and procedures for the ground personnel and ground infrastructure necessary for the long-term storage, security, maintenance, transportation, preparation, installation and safe removal of the nuclear engines before they are configured into a missile immediately prior to launch.

2. **Weight burden of radiation shields**. The nuclear reactor needs to be designed with heavy shielding to protect the ground crews and on-board electronics from the effects of radiation from the nuclear fuel rods. This can be a significant mass burden that impacts the available payload and flight performance.

3. **Reactor stress from increases in airflow temperature and pressure**. There are stresses associated with the necessary drop in the air pressure as the air flows through the hot nuclear reactor. The nuclear thermal energy can heat the air and engine wall temperatures up to the order of about 1000 to 1200 degrees Celsius[23] and this increases the air pressure in the order of hundreds

of psi, similar to a jet turbine exhaust. This in turn causes the airflow to increase the mechanical stress in the engine components, nuclear reactor, and airframe structure.

4. **Reactor thermal control and management.** The heat generated by the nuclear reactor, including the heated airflow will be transferred to the airframe through the combustion chamber and exhaust nozzle. Traditional reactor systems would normally be configured with a cooling system to direct coolant to dispel heat away from the nuclear reactor rods. Without a coolant system, this heat needs to be absorbed and removed by airflow.

5. **Hot air oxidation and material corrosion**. When air is heated to high temperatures, a chemical reaction can occur between metal and atmospheric oxygen that can cause corrosion of the interior metal walls of the engine that are exposed to the nuclear heating. Novel active anticorrosive metal coatings, such as titanium dioxide (TiO2) can provide options to lessen or delay the damaging effects of hot oxidation corrosion.[24] Corrosion can be a determent for the life of the missile, its useability and its mission.

6. **High speed pitting and material corrosion.** Radiation and extreme heat can have a corrosive effect on the mechanical qualities of some structural metals and ceramics, if not designed with protection. Impurities will exist in the airflow that is drawn into the reactor and heated to high temperatures. The heated impurities are then accelerated by the heat and expansion effects and impact the interior surfaces of the expansion chamber and exhaust nozzle causing materials to deteriorate, thus degrading the performance of engineered parts. Corrosion will have accumulating effects, on the vehicle's materials and mission life, the extent of which will depend on the duration of flight and reactor operation. Damage from pitting can be a determent for the life of the missile, its useability and its mission.

Electromagnetic Effects of Nuclear Fission Products on Missile Systems

The fission reactions to split the atomic nuclei releases free neutrons as fast travelling atomic particles (ie neutrons and smaller atoms split from U-235 nuclei) and gamma radiation. Radiation can be either ionizing or non-ionizing, depending on how it affects matter. Non-ionizing radiation includes visible light, infrared, radar, microwaves, and radio waves in the lower frequency part of the electromagnetic spectrum; this type of radiation transfers energy into the materials through which it passes but is not sufficient energy to remove electrons from atoms. Ionizing radiation (eg gamma rays, x-rays and cosmic rays) occur in the higher frequencies part of the electronic spectrum and are much more energetic than non-ionizing radiation.[25]

The effects of gamma radiation and ionisation are explained further in annex A.

The Environment Surrounding the Nuclear-Engine

When considering the likely natures of the nuclear environment around the nuclear engine of a missile, there is likely to be minimal radiation protective shielding, in order to reduce the weight burden on the size and mass of the propulsion system need to propel the missile's mass. Thus, the fission reaction at the nuclear reactor will produce the following nuclear effects:

1. Energetic **gamma rays** may radiate in all directions to penetrate and disrupt unprotected electronic and computer system components and cause radiation injuries to nearby unprotected personnel.
2. **Neutrons** can radiate in all directions and penetrate solid objects and nearby unprotected personnel.
3. Fissile materials and fission products (ie **radioisotopes**), are created within the nuclear fuel rods. The degradation of the fuel rods may cause radioisotopes to escape and/or be released directly into the airflow and be ejected into the atmosphere with the jet exhaust.
4. Particulates, aerosols and air molecules from the atmosphere that pass through the nuclear reactor may be irradiated by its ionising

and radiation effects to form additional **radioisotopes** sourced from materials outside the reactor fuel. These radioisotopes will then be carried by the airflow and be ejected into the atmosphere through the jet exhaust.

Design differences for subsonic, supersonic and hypersonic flight

The external appearance and shape of the missile can be used estimate its optimum operating speed; wing and airframe designs are distinctly different when optimised for slow speed, subsonic, supersonic, and hypersonic speeds.

1. **Hypersonic missiles** are shaped to be long and slender down the full length of the fuselage with small control fins mounted further back (refer X-51A Waverider in Table 1). Stable hypersonic flight is critically dependent on keeping the main wingtips out of the nose shock wave; the shock wave angle increases to push the edge of the shock wave closer to the fuselage at higher supersonic speeds. Wingtips that penetrate the shock wave will experience shockwave drag and this, in turn, could cause in-flight instability and additional stress on the vehicle's structure. Designs for hypersonic vehicles must also eliminate unnecessary external protuberances that will generate their own shockwaves and add additional drag and structural stress wherever the shock wave contacts the missile body. Thus, hypersonic missiles are distinctive in their smooth, conformal, and integrated airframe, aerodynamic lifting surface. Air-breathing variants are configured with an external booster rocket and a scramjet as the main engine for a cruise trajectory.

2. **Supersonic missiles** (refer YJ-12 ASCM in Table 1) are distinctive in using designs with a very sharp pointed nose cone to penetrate the leading sonic shockwave. They appear with a long slender body. Short fin wings are used to generate lift that are swept back to avoid penetrating the main shockwave originating at the vehicle nose; smaller control fins are usually mounted to the rear, or thrust vector controls may be fitted to the rear of the exhaust, in order

to control the missile's trajectory in flight. Supersonic missiles are normally configured with an external booster rocket and a ramjet as the main engine for the cruise trajectory.

3. **Subsonic missiles** (refer AGM-158 JASSM in Table 1). Subsonic missiles typically have a smooth rounded airframe to reduce the effects of aerodynamic drag. Larger wings are needed to aerodynamically generate lift; large control surfaces are used to aerodynamically control the flight, configured with an external rocket booster for land launch or carried for air-launch from a strike aircraft; a turbine (ie turbojet or turbofan) engine is used to fly a cruise trajectory.

The external appearance of the airframe design, main wing, and aerodynamic flight controls for the SSC-X-9 Skyfall suggest that its likely to be a cruise missile designed for subsonic flight at low to medium altitudes. If configured with a nuclear-powered engine, the engine design is likely to be a nuclear-powered jet turbine. Since it cannot achieve its cruise speed without a boost, it requires an external rocket booster, most likely using a ground launch site and rely on a heavy missile canister to mitigate against radiation hazards to ground personnel. The missile is likely to be configured only with the minimum radiation protection measures around the nuclear reactor to enable the correct functioning of on-board electronic systems, in order to reduce the all-up missile weight. The physical appearance and size of the missile might indicate that this minimum protection may make it unlikely to be compatible for safe carriage and launch from a crewed warship, submarine, or aircraft.

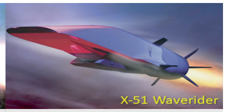
	 AGM-158 Joint Air-to-Surface Standoff Missile (JASSM)[26]	 YJ-12 Anti-Ship Cruise Missile[27]	 X-51A Waverider[28]
Acceleration from zero to operating speed	Air-launched	External booster rocket	Air-launched plus external booster rocket
Engine for cruising speed	Air-breathing jet turbine	Air-breathing ramjet	Air-breathing scramjet
Cruise speed	M0.85 subsonic	M3.0 supersonic	M6.0 hypersonic
Time to travel 300/1000km	16.7/55.7 min	4.7/15.8 min	2.4/7.9 min
Cruise altitude	low- to medium-level (nap of the earth trajectory)	Sea-skimming or medium-level	high-level
Aerodynamic Lift	Lift from main wing	Lift from small fin wings, positioned out of shock wave cone	Lift from shaped integrated lifting body (ie fuselage)
Flight Controls	Aerodynamic control surfaces	Aerodynamic control fins	Aerodynamic control fins
Navigation: mid-course, terminal	INS/GPS EO/GPS	INS/GPS radar	INS INS
Warhead	conventional high-explosive	conventional high-explosive or nuclear	conventional high-explosive or kinetic energy
Self-protection	stealth; evasive planned routing	low-altitude; supersonic speed	hypersonic speed
User	Australia, USA	China	USA

Table 1. Comparing SSC-X-9 Skyfall against typical design characteristics for air-breathing subsonic, supersonic and hypersonic missiles.[29]

Missile systems design principles

Assured System Safety, Reliability, and Security

When comparing the typical mission durations of nuclear and non-nuclear powered missiles, the timeframes associated with the nuclear missile extends options for the mission to potentially fly for decades or until a critical component of the system fails.

The design requirements for the missile would need to factor the survivability of launch and long-range flight, through varied environmental conditions while continuing to perform reliably. Additionally, the security of a potentially nuclear warhead, would require that the quality of the missile system design and engineering will need to be of a higher standard in order to assure the correct, reliable, and continuing functioning of the missile, potentially for an extraordinary long mission-life.

Additionally, the missile system may be designed with redundancy in its critical components to help increase its reliability after extended operations. It will be important to monitor systems status and health, necessitating datalink communications that reach back to the missile operator.

Designed with Relying on Consumable Items

Normally, missiles on-board systems contain a finite quantity of consumables such as jet fuel, lubricants, infrared seeker coolant, pressurised gas for moving the flight control surfaces, etc. The quantity and rate of use of available on-board consumables may determine the maximum life of the missile, similar to on orbit systems in space. The SSC-X-9 Skyfall may be deliberately designed with components that avoid the uses of consumable materials. This would enable the missile to function for very long periods without the risk of a component system failing once the supply of consumable materials expires.

For example, the flight control system might be designed to use electro-mechanical devices and pushrods for the guidance, navigation and control system to actuate the aerodynamic flight control surfaces, instead of using a cold-gas generator to generate pressurised gas to drive hydraulic actuators; magnetic engine bearings cannot eliminate the need for lubricating oil[30]. Additionally, design assumption of unlimited electrical power from the nuclear-powered engine could potentially be leveraged.

Airframe structure and materials

The extremely long flight durations of long-endurance missions may require additional strengthening and tighter quality control of systems engineering than normally required for shorter duration air missions. Long-endurance flights in the air environment can expose the missile to sustained shocks and stresses from external environmental forces acting on the vehicle and subsystems. Additionally, engine vibration, aeroelasticity effects and thermal energy will act on the internal systems. Extra effort will be required to ensure more robust designs to assure the continued correct functioning of both the nuclear reactor and the missile during long sustained flight.

The longer the flight duration, the greater will be the risk of a failure occurring within a component and/or the total system. Two particularly likely causes for systems failure, for a nuclear-engine missile, could be:

1. **Airframe thermal control and management**. The heat generated by the nuclear reactor, and the heated airflow, will transfer to the airframe through the combustion chamber, exhaust nozzle or insufficient shielding. Traditional propulsion systems would be configured with a cooling system to direct cool air or unused liquid propellant to absorb some of the heat before it is directed into the combustion chamber. Without such designs for transferring and control heat, the thermal energy is absorbed by the missile and relies on external airflow being cooler in order to transfer the heat from the missile to the surrounding air. Missile parts that cannot be cooled will need to be designed with a specialised heat resistant material.

2. **Vibration-induced stress from flight**. Aerodynamic flight and manoeuvres cause changes in stresses throughout the vehicle. Stress loadings, especially on the wings, can vary with the air density at altitude and the frequency and roughness of flight manoeuvres. This flight-induced mechanical stress can be transferred to the nuclear reactor. Mechanical stress over a long period of time, without inspection and servicing, will eventually accumulate fatigue on the missile until catastrophic failure.

Low observable (LO) technology has become an increasingly fundamental design feature of many air vehicles. The use of LO technology can reduce its detectability from an adversary's sensors, typically aimed at lowering the detection threshold of radar, infrared, visual and acoustic detection systems. Typical LO technologies are normally designed into missiles, ranging from shaping to radar-absorbing materials and smoothed, low-angled reflecting structures tailored to the likely threat sensors.

The external shape could indicate that the SSC-X-9 Skyfall is shaped to reflect radar signals away from the direction of the radar transmitter/receiver. It is difficult to assess if the missile exterior is coated with a radar absorbent material.

Modern high-performance LO missile and aircraft are designed with an 'S' shaped air intake for drawing air into the jet turbine. The 'S' describes the offset between the centreline of the air intake and the axial centreline of the jet turbine (refer Figure 6). This physical offset in alignment enables the jet turbine blades to be hidden from a radar sensor looking from the forward direction.

Since the jet turbine is not combusting a hydrocarbon fuel like in a conventional jet turbine, the turbine exhaust is likely to be smoke-free and offer a low-visibility signature in the visible spectrum. The heat from the hot exhaust gas will project an infrared signature which will trail behind the missile in flight for as long as the ejected exhaust remains hotter than the ambient air temperature around it.

Guidance, Navigation and Control

Long-range missiles are typically equipped with an inertial navigation system (INS) for use in guiding them along the flight route running between navigation waypoints, programmed prior to launch. It is likely that the INS is coupled supported by positioning signals from GPS or (in the case of the SSC-X-9) GLONASS global navigation satellite systems to check and correct the INS for any systems drift over long flight distances.

The mission route is expected to have been pre-set following the preflight mission planning. The navigation system will probably use the uploaded mission plan, with the flight trajectory, for use as a reference to autonomously check the missile's position error as measured by the onboard coupled INS/GPS – the measured difference against the planned trajectory indicates the error correction that is used to adjust the flight controls and steer the missile back onto the planned trajectory. The GPS and GLONASS receiver may be operating intermittently to prevent countermeasure effects by an adversary; the INS cannot be jammed directly by external signals and functions continuously.

Long-range missions are likely to be configured with a communications system that enables the missile operator to intervene or update the mission. The missile's nuclear reactor may be configured with lightweight shielding only to protect the electronic component and radio signals in the forward section of the missile from radiation interference. The missile communications system is likely to be capable of using the following on-board communications systems:

1. forward pointing antenna(s) for "see and avoid" sensor, radar, and communications;
2. downwards pointing antenna for terrain avoidance radar; and
3. skywards pointing antenna for satellite-relayed datalink communications and GPS or GLONASS.

Communications with the missile from the rear sector is unlikely since a rearward pointing antenna will be pointing through the ionising radiation present in the jet exhaust and trailing wake. Terrestrial-based communications are more likely to be effective if oriented to reach the forward section of the missile. Otherwise, the satellite communications will enable long-range and global communications into the skywards pointing antenna.

The operation of on-board radar systems can be a significant burden on stored electrical energy systems, constraining their operation. It may be plausible that the on-board nuclear reactor will have adequate capacity to both sustain unlimited propulsion for the vehicle and unlimited generation of electrical power for components and subsystems.

The navigation system would rely on datalink communications for mid-course mission updates and corrections, including:

1. Mission abort in order to divert airframe to a safe jettison area for disposal;

2. Update the flight routing for terrain and threat avoidance based on updated intelligence assessments; and

3. Update and changes to mission parameters.

Missile warhead options and damage mechanisms

The long-range cruise missile design of the SSC-X-9 Skyfall appearance makes it likely (similarly to the US Tomahawk cruise missile) to be capable of being configured with either a nuclear or a high-explosive (HE) warhead. Because the missile is nuclear powered, a HE warhead will likely include incidental radiation effects, due to the proximity of the reactor. The likely damage mechanisms with either warhead will be:

1. Nuclear warhead – radiation (electromagnetic, ionising, and non-ionising), air pressure blast, heat (tens of millions of degrees Celsius), and fragmentation.
2. High-explosive – blast, heat (thousands of degrees Celsius), and fragmentation.

One of the most important factors in maintaining an effective deterrent capability is assuring that a weapon will operate only when it is intended. The possible fuse options for controlling the warhead functioning and effects at the target may be any or all of the following options:

1. Proximity fuse for airburst detonation over the target or target area;
2. Impact fuse for detonation on impact with the surface of the ground or target;

3. Delayed impact fuse for penetrating targets that are hardened, underground, or underwater.

Note: Australia does not possess any nuclear weapons and is not seeking to become a nuclear weapons state. Australia's core obligations as a non-nuclear weapon state are set out in the Nuclear Non-Proliferation Treaty (NPT)[31]. This includes a solemn undertaking not to acquire nuclear weapons.

Nuclear reactor collateral damage

The decision to launch an SSC-X-9 Skyfall missile represents an acceptance of causing nuclear contamination in the environment irrespective of whether the missile is configured with a nuclear warhead. Nuclear contamination will spread from the remnants of the nuclear fuel rods in the atomic engine and radioactive material being ejected with the jet exhaust. The missile will likely cause nuclear reactor contamination along the flight trajectory and at the target. If a missiles mission is aborted and the warhead is rendered safe, the missile will still pose a radioactive hazard with a hot nuclear reactor and unarmed nuclear warhead being jettisoned with the missile.

The correct functioning of the nuclear warhead damage at the target, will overwhelm any level of damage from the remnants of the nuclear reactor. If the missile is configured with a conventional HE warhead, the blast/heat/fragmentation damage at the target or jettison area will be contaminated by the remnants from the nuclear reactor.

Missile Operational Employment

Missile Mission Planning

The SSC-X-9 Skyfall is promoted by the Russians as being able to potentially fly forever. In the current era of digitised mission planning systems and interconnected environments of various airspace users. The mission planning system will require significant quantities of available geospatial data and situational awareness information in order to deconflict the missiles flightpath from terrestrial and environmental obstacles and the changes occurring in and around the theatre of operations that are likely to occur during the long flight duration (refer Figure 7). Furthermore, due regard and sovereignty considerations should be given to flying the missile over populated areas and environments that are sensitive to the radioactive contamination ejected from the missile along its extended and potentially repeating flight trajectories.

Missile Modes of Operation

The missile is likely to be designed to perform in the following system operating modes:

1. **Disassembled missile in storage**. It is likely that, owing to the radiation protection measures needed, the nuclear-powered engine and nuclear warhead (if fitted) is stored separately from the missile airframe.

2. **Assembled missile in the canister**. It is assumed that the nuclear-powered engine is installed to the missile airframe immediately prior to its launch. The missile canister could be expected to provide the necessary radiation protection for the ground personnel, transport systems and ground infrastructure.

3. **Missile zero-state (dormant) mode.** The zero-state might be represented by the assembled missile being situated at the ground launch site with the mission data files uploaded into the missile guidance, navigation and control system, ready for launch.

4. **Missile in flight (mission execution) mode**. The missile flight mode can be broken down further into the following indicative phases:

   (a) **Launch phase**. The external rocket booster is initiated to boost the static missile to the minimum operating speed for the nuclear-powered jet turbine to function and provide enough thrust to propel the missile and make the aerodynamic flight controls function. The missile is unlikely to be planned for launch from a crewed aircraft, warship, or submarine owing to the radiation hazards from the hot nuclear fuel rods in the missile's nuclear-powered engine.

   (b) **Cruise Phase**. The missile navigates autonomously along its pre-set course and trajectory with navigation system accuracy provided by GPS or GLONASS. The missile might be configured with an electronic support system that provides a 'sense and avoid' capability for the missile to autonomously evade adversary detection systems (refer Figure 7)[32].

(c) **Holding phase**. It is likely that a missile that is capable of nearly unlimited flight time will require communication with a ground station to refine flight paths or re-target. Furthermore, the missile(s) may be launched into a holding pattern at a forward location to await updates on the nominated targets.

(d) **Terminal attack phase**. The missile is likely to be programmed to fly in a holding pattern pending receipt of a command signal to proceed to the target as a single missile or a missile salvo. The missile would probably guide to the target using GPS or GLONASS for precision guidance to the geospatial coordinates for the target. The missile is unlikely to operate electro-optical guidance that relies on television cameras that are constrained by weather and environment conditions or infrared which consumes a coolant for the seeker from a finite on-board supply.

5. **Missile contingency (abort) mode**. The missile is likely to be programmed with a number of decision checkpoints where, if the conditions are not met, the missile may be selected to autonomously either proceed with the priority mission plan or divert to a planned safe jettison area for impact.

Potential Concepts of Operations (CONOPS)

The mission effects that are possible with the nuclear-engine SSC-X-9 Skyfall could be used in new ways that previous generations of missiles were unable to. The potential for realising unlimited engine performance negates the requirements for using transport vehicles to carry the missiles close to or within a theatre of operations.

The following roles might be applicable to the development of any SSC-X-9 Skyfall CONOPS:

1. **Deterrence.**[33] Using information operations to describe both the missile's capabilities, and a publicly stated intent to employ it, in

a ploy to convince a potential aggressor that the consequences of coercion or armed conflict would outweigh the potential gains – this is the current state of affairs, following Russia's announcement of this capability.

2. **Strategic strike.**[34] The planning and execution of kinetic effects missions for the missile warhead to inflict deliberate damage against an adversary's power base in order to meet operational needs.

3. **Anti-access and area denial (A2/AD).**[35] Forward deploying the missile launchers and/or employing information operations, to limit an adversary's freedom of action within an operational area.

4. **Forward presence.**[36] A strategic choice to launch missiles into a holding pattern located at a distance from the home base or stationed overseas to establish a 'forward presence' in order to demonstrate national resolve, dissuade potential adversaries, and enhance the ability to rapidly respond to contingencies.

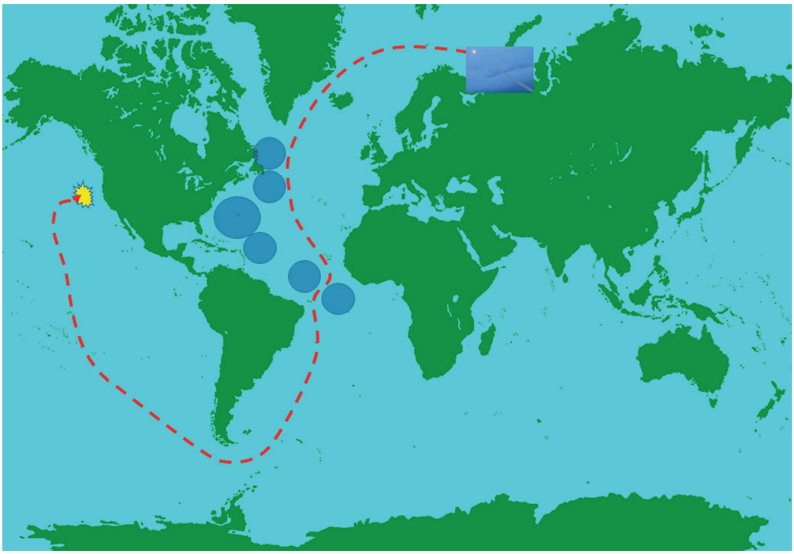


Figure 7. Depiction of the flight performance of SSC-X-9 Skyfall, as briefed by Russia's President Putin in his 2018 State of the Nation address to the Kremlin.[37]

CONOPS for Deterrence

The deterrence effect will be based on managing the perceived threat of an operationalised nuclear-powered missile that could potentially fly an unlimited distance to deliver a nuclear warhead and defeat any air defence systems by flying a globally circuitous route to penetrate a weakness and/or loiter until such time that the battlespace presents a favourable circumstance to reach the target. Furthermore, the perceived threat is exacerbated by the common knowledge that, once launched it will definitely dispense nuclear fission waste products and radiation hazards for the entire duration of its flight operation. Additionally, the impact at the nominated target, even if aborted and diverted to designated safe jettison area, will also cause uncontrolled nuclear contamination of the target area.

The risks of collateral nuclear damage to third party countries and their regional interests, may also encourage allies and collective partners, to more rapidly negotiate a peaceful resolution in order to limit the employment of such a weapon through foreign and international territories during its global flight paths.

CONOPS for Strategic Strike

The missile flight routing to the target is planned in order to optimise its survivability against environmental obstacles and adversary air defence systems. The unlimited range of the SSC-X-9 Skyfall enables it to fly a long circuitous route in order to: evade mobile air defences; avoid fixed detection systems; reduce risks of nuclear contamination to populated areas by flying over international waters far away from the coastlines; and, fly a holding pattern to delay its arrival at the target until a specific time.

The precision guided cruise missile may rely on GLONASS satellite navigation for measuring its navigation accuracy. A missile datalink system, shielded from the nuclear-engine could receive mid-course mission updates to enable a mission abort and diversion to a safe jettison area for impact or receive updated target data.

The missile can be operated as a single missile or a salvo, flying in trail or arriving at the target at the same time from different directions, in order to overwhelm air defence systems. The possible uses of nuclear or HE warheads suggests the primary objectives may be fixed unitary targets, such as strategically significant structures and infrastructure or warships operating as part of a naval task group.

CONOPS for Anti-Access and Aarea Denial (A2/AD)

A2/AD capabilities are designed either to prevent an adversary's access to a particular region (anti-access) or to contest its freedom of movement within that theatre (area denial). The A2/AD concept has its origins in the perception of China's strategy for securing the South Chain Sea islands and sea-lines of communications. China's A2/AD uses "a series of interrelated missile, sensor, guidance, and other technologies designed to deny freedom of movement" [38] to keep potential adversaries, including the US, from intervening in any conflict situated off China's coast, or from attacking the Chinese mainland through the South China Sea.

The coastal deployment of long-range SSC-X-9 Skyfall missile launchers could potentially be used to extend the reach of land based-defences from sovereign territories, without the need to forward deploy more valuable assets as launch vehicles to penetrate close to the adversary.

CONOPS for Forward Presence

A strategic choice to deliberately launch missiles into a remote holding pattern located at a distance from the home base or stationed overseas may establish a 'forward presence' in order to demonstrate national resolve and reduce response times to an adversary's actions. Additionally, the knowledge of the forward presence may serve to strengthen alliances, dissuade other potential adversaries, and enhance the ability to respond quickly to changing contingencies.

This action utilises the overt threat of force to coerce an adversary to adopt a certain pattern of behaviour against their wishes. This is analogous to the concept of 'gunboat diplomacy' which can refer to the ways that states conducted their foreign affairs in the 19th century. In order to achieve their foreign policy goals, states such as the Great Britain and Germany used their combat proven and powerful navies - frequently deployed their naval forces in order to intimidate and coerce weaker states with the threat of military intervention.[39]

The forward presence CONOPS could also be used to improve the responsiveness of long-range strikes against dynamic changes in strategic targets or changing dynamics in theatre. The forward presence enables a flying arsenal of missile to loiter closer to the battlefield, awaiting targeting data and commands to strike, using communications with the missiles to provide mid-course updates.

A forward deployed airborne arsenal could remain on-station, within a defended or benign theatre environment, and be continually available to respond to target nominations, for the flying life of the missile. Urgent strikes can be launched from the loitering flying arsenal in lieu of using deployments of air/land/sea/submarine missile launch platforms. This might be analogous to US Air Force B-1B and B-52H long-range heavy strategic bombers being used as 'arsenal planes'[40] to forward deploy closer to their targets. The bombers are capable of carrying a heavy bomb-bay load of precision guided munitions that can be released individually or in a salvo, on demand from discrete airborne and ground borne joint tactical air controllers. However, a missile like the SSC-X-9 Skyfall could loiter for longer with no risk of the crew being threatened or becoming fatigued.

Conclusion

The potential operationalisation of the SSC-X-9 Skyfall as a nuclear-powered missile may be a Russian strategic innovation to exploit nuclear technology and disrupt conventional air power without necessarily introducing a new nuclear weapon. Russia may gain a strategic edge with a nuclear-powered missile that is potentially capable of flying for an unlimited duration over an unlimited range until the system is either commanded to strike its objective or it breaks down in flight. It may be capable of flying circuitous routes around the globe and between theatres of operations to find a vulnerable entry to bypass defence systems.

The experimental SSC-X-9 Skyfall is likely to be a nuclear-powered, subsonic long-range, INS/GLONASS guided low to mid altitude cruise missile with the ability to carry either a nuclear or HE warhead. The nuclear engine itself does not necessarily categorise the weapon as a WMD, since it is purpose-designed as the propulsion system. Any nuclear warhead, a purpose-designed mechanism for mass destruction that is the determinant for categorising a WMD.

The nuclear-powered jet turbine propulsion and aerodynamic flight controls are not effective until the missile is launched and at its operating speed; it needs some form of rocket booster to accelerate it from zero to the turbine's minimum operating speed. The nuclear engine uses air as its propellant. Thus, it becomes theoretically possible for the nuclear-engine vehicle to remain airborne for as long as the nuclear reactor is functioning, air is available, and the vehicle remains intact and functioning.

The long-range/long-duration enables options for a raft of new concepts of operations, beyond the accepted concept for strategic strike. The ability to fly a long and circuitous flight route enables the missile to avoid and evade air defence systems and ingress towards a target from any direction. Furthermore, the ability to loiter, seemingly endlessly enables the user to deploy a single or salvo of missiles into a forward position in order to deny, deter or coerce an adversary.

It is unlikely that this missile is designed to be a fire-and-forget missile in other than a contingency mode of operations; it will most likely be configured with a communications capability to provide options for remotely issuing commands to commit the missile to an attack, execute a mission abort, update the mission, and/or divert the missile onto an alternative mission.

Mission planners will need to have a much broader geospatial awareness of the air operating environment for the missile mission plan that will extend to global dimensions for up to days and weeks beyond the missile's planned launch time and location. Additionally, operators will need to be monitoring this extended environment for changes in the strategic and tactical situations which may affect the mission intent. Mission planners need to be cognisant of the potential collateral damage from the radioisotope contaminated exhaust gases when planning the flight route – to avoid populated and radiation sensitive environments (populations, drinking water reservoirs, agriculture, etc).

This technology in its current crude form may represent a weapon of last resort, the commitment by any nation to launch a nuclear-engine missile is a commitment to transgress current international norms in ignoring the potential risks and collateral damage of releasing nuclear materials into the environment including the political fallout of an unplanned failure of one of these weapons and the catastrophic damage it could have on an innocent third party.

Annex A

Gamma Radiation and Ionisation Effects

Gamma rays are very high frequency (ie greater than 10 million gigahertz) and therefore have very high energy electromagnetic radiation. The frequency range is beyond the part of the spectrum that is normally used by satellite communications and global navigation satellite system. However, a gamma ray can cause ionising effects in the substance through which it passes. Ionisation is the subatomic quantum process of energetic gamma rays knocking electrons out of stable atoms to form ions; ions are electrically charged particles that can inadvertently generate an electrical current.

Gamma radiation may irradiate exposed and non-hardened (eg non-shielded) electronic equipment to cause ionisation within the electronic componentry that generates unwanted electrical signals. These unplanned and spurious electrical signals may carry enough energy to electrically overload and damage an electronic component and/or disrupt the correct functioning of an electrical system, causing it to malfunction.

The different ionisation effects of radiation can be categorised[41] as:

1. Total Ionizing Dose (TID) causes the build-up of unwanted electrical charges at electrical system interfaces and connections that could introduce spurious and unwanted electrical signals into an electronic system. These spurious signals can disrupt data and control signals, causing the component or system to functioning incorrectly. If the energy level is high enough, and the system is not hardened or protected, the TID may cause physical damage to the electrical connections and system components.

2. Single Event Effect (SEE) is caused by ionised charged particles with sufficient electrical energy to discharge an electrical current and trigger changes in the logic state of unprotected computer memory bits, disrupting the normal functioning of the computer using that memory system[42].

Normally, gamma radiation could be blocked by several feet of construction concrete or a dense material such as lead sheeting that is a few centimetres thick.[43] These protective shields and containment constructions are typically only viable in the large infrastructure that can be configured into a building or large ship/submarine.

Neutrons and Ionising Radiation Effects

Neutrons are high-speed subatomic particles that penetrate other materials and cause atomic nuclei to split into smaller mass isotopes that don't normally exist in a naturally stable form. Since the isotopes are unstable, they will normally decay or spontaneously disintegrate, emitting radiation in the process.[44] Thus, neutrons are the only type of radiation which can make non-radioactive materials become radioactive through subatomic collisions. Additionally, neutron radiation is considered the most severe and dangerous radiation to human tissue.

Neutrons are able to travel great distances in air and can penetrate readily solid matter to collide with atomic nuclei. Normally, neutron radiation from nuclear reactors would be blocked by thick hydrogen-containing materials (such as concrete or water) to provide a shield to contain them[45]. Additionally, chemical elements such as boron are used in the shield construction because they readily slow and absorb neutrons. These protective water or concrete shield constructions are typically only viable in the large infrastructure that can be configured into a building or large ship/submarine.

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Nuclear Engine Air Power

Russia is experimenting with a new missile it has named the 9M730 Burevestnik. NATO has given it the designation SSC-X-9 Skyfall. After a nuclear contamination incident in Russia was reported in August 2019, international analysts concluded that Russian scientists were working on a miniaturised nuclear powered engine that accidentally exploded, suggesting that they were testing an experimental cruise missile powered by a small nuclear reactor.

The possibility of an extremely long-endurance cruise missile was first revealed during the 2018 State of the Nation address by Russia's President. The operationalisation of a nuclear-powered missile, enabling extremely long-range missile trajectories, may disrupt traditional air power doctrine, traditional thinking of designs and functions of air defence systems, and norms for the risks of nuclear contamination. Nuclear engines may be a game-changer that disrupt both technological and political strategic-thinking, potentially necessitating a need to enhance the delivery and effectiveness of air power through new concepts in multi-domain operations.