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Workshop on potential release scenarios from flight
testing of nuclear-powered flying vehicles

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Abstract

In recent years, there have been claims that a nuclear-reactor-powered cruise missile is under development in Russia. There is a need to consider the radiological implications, if any, for the Nordic countries. The NUPFLIGHT workshop was held in Solna (Stockholm) on June 15, 2022, to discuss and collate the current state of knowledge about nuclear reactors used to power flying vehicles, or knowledge that can be extrapolated into this area. The focus was on the possible consequences of accidents during flight testing, and potential release scenarios. While there has been some work on risks related to maritime nuclear propulsion, it was expected that a nuclear reactor used to power a flying vehicle such as a cruise missile would have distinct features impacting the assessment of potential releases in case of an accident or even during planned operations. Little is known about engineering details relating to such reactors, but it was hoped that considerations of general principles such as power requirements, flight times, temperatures, weight and the properties of conceivable fuel materials and designs could be used to bound the problem and assist in improving the confidence in risk assessments.

This report summarizes the NUPFLIGHT workshop and also reflects post-workshop comments and refinements.

Key words

Nuclear reactors, nuclear-powered missiles, accident scenarios

Workshop on Potential release scenarios from flight testing of nuclear-powered flying vehicles

Report from the NKS-B NUPFLIGHT activity (Contract: AFT B(22)7)

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Table of contents

	Page
1. Introduction	4
2. Workshop programme	4
3. Workshop participants	5
4. Summary of presentations	6
5. Workshop discussions	9
5.1 General considerations	9
5.2 Reactor properties	9
5.3 Scenarios	10
5.4 Possible parallels and comparisons	11
5.5 Possible questions from the public and from policy-makers	12
6. Conclusions	12
7. References	13

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1. Introduction

In recent years, there have been claims that a nuclear-reactor-powered cruise missile is under development in Russia, and indeed has been successfully flight tested. Although there are no reliable independent open reports confirming the precise status of such a project, it is clear that there is a need to consider the radiological implications, if any, for the Nordic countries, particularly those with territories close to Russian Arctic testing areas.

It was therefore proposed that a workshop would be held, bringing together Nordic authorities responsible for nuclear and radiological emergency preparedness, to discuss and collate the current state of knowledge about nuclear reactors used to power flying vehicles, or knowledge that can be extrapolated into this area. The focus would be on the possible consequences of accidents during flight testing, and potential release scenarios. While there has been some work on risks related to maritime nuclear propulsion, and the outcomes of *e.g.* the NKS-B CRESCENT activity was to be leveraged where possible, it was expected that a nuclear reactor used to power a flying vehicle such as a cruise missile would have distinct features impacting the assessment of potential releases in case of an accident or even during planned operations.

Little is known about engineering details relating to such reactors, which makes the problem of estimating a source term challenging. Nevertheless, it was hoped that considerations of general principles such as power requirements, flight times, temperatures, weight and the properties of conceivable fuel materials and designs could be used to bound the problem and assist in improving the confidence in risk assessments.

Consequently, the NUPFLIGHT workshop on potential release scenarios from flight testing of nuclear-powered flying vehicles was held in Solna (Stockholm) on June 15, 2022. This report summarizes the workshop and also reflects post-workshop comments and refinements.

The NKS-B NUPFLIGHT activity was co-ordinated by Swedish Radiation Safety Authority (SSM) and was a collaboration between the following organizations (in alphabetical order):

Norwegian Radiation and Nuclear Safety Authority (DSA). Contact person: Øyvind Gjølme Selnæs

Swedish Defence Research Agency (FOI). Contact person: Kennet Lidström

Icelandic Radiation Safety Authority (IRSA). Contact person: Gísli Jónsson

Swedish Meteorological and Hydrological Institute (SMHI). Contact person: Lennart Robertson

Swedish Radiation Safety Authority (SSM). Activity co-ordinator: Anders Axelsson

The Norwegian Defence Research Establishment (FFI), the Finnish Radiation and Nuclear Safety Authority (STUK) and the Finnish Defence Forces also attended the workshop.

2. Workshop programme

The NKS-B NUPFLIGHT workshop was held at the SSM office in Solna, Sweden, on June 15, 2022. Remote participation was also offered and was used by several participants.

09:00 – 09:30 Introductions, topics for discussion (Anders Axelsson, SSM)

09:30 – 10:00 What is known about the *Burevestnik* missile? (Elin Enger, FFI)

Coffee

10:30 – 11:00 Source terms. What we need to know on fuel and reactor design (Odd Runevall, SSM)

11:00 – 11:30 Capabilities of a reactor powered airborne vehicle (Fredrik Nielsen, FOI)

11:30 – 12:00 Summary of the recent NKS-B CRESCENT workshop in Iceland. The Icelandic perspective (Gísli Jónsson, IRSA)

Lunch

13:00 – 13:30 Relevant overlaps and lessons from the NKS-B CRESCENT project (Øyvind Gjølme Selnæs, DSA)

13:30 – 14:00 Transport modelling – Specification needs (Lennart Robertson, SMHI)

Group photo

14:15 – 14:45 Assessments and response to the Nyonsoksa radiation accident (Mikael Moring, STUK)

Coffee break

15:15 – 16:00 Any/all: Short briefs on assessments performed

16:00 – 17:00 All: Discussions aimed at outlining conclusions and report contents

3. Workshop participants

Participating organizations and participants are given below in alphabetical order.

DSA (Norwegian Radiation and Nuclear Safety Authority)

Skjalg Are Fagerjord

Øyvind Gjølme Selnæs

FFI (Norwegian Defence Research Establishment)

Elin Enger

Finnish Defence Forces

Tuuli Haataja (remote)

Irene Hurmerinta (remote)

Helmiina Äimälä (remote)

FOI (Swedish Defence Research Agency)

Andreas Forsberg

Kennet Lidström

Fredrik Nielsen

IRSA (Icelandic Radiation Safety Authority)

Gísli Jónsson

SMHI (Swedish Meteorological and Hydrological Institute)

Lennart Robertson

SSM (Swedish Radiation Safety Authority)

Anders Axelsson

Lars Axelsson

Anna Maria Blixt Buhr

Jonas Lindgren

Odd Runevall

Britt-Inger Wede

STUK (Finnish Radiation and Nuclear Safety Authority)

Aleksi Mattila

Mikael Moring

4. Summary of presentations

Each 30-minute presentation slot included time for questions and discussion. In this report, the content and outcomes of discussions is amalgamated and organized separately in the section following. This section contains only summaries of the material presented.

Introduction. Topics for discussion (Anders Axelsson, SSM)

SSM introduced the aims and structure of the workshop. The aim is to contribute to realistic risk assessments related to radiological risks from flight testing of nuclear-powered flying vehicles. In particular, the workshop should contribute by bringing together, sharing and arranging knowledge and approaches, identify things that could be done to improve knowledge and capabilities and build a network for future collaboration and information exchange.

Several “entry points” to discussing the subject matter of the workshop were suggested, not necessarily “orthogonal” or separable but simply ways to approach the subject. These were scenario and engineering considerations (i.e. properties of vehicle and reactor; mission, flight and accident parameters), source terms (i.e. core inventory; release scenarios; flight and accident scenarios), dispersion and dose modelling (i.e. dispersion calculations; risk distances; consequences on site; consequences in Nordic countries), risk assessment, protection strategies and communication, detection and investigation of an event involving a nuclear-powered cruise missile (i.e. sources of data and information; airborne radioactivity and identifying characteristics of such signatures).

What is known about the *Burevestnik* missile? (Elin Enger, FFI)

FFI presented information from open sources on the Russian *Burevestnik* nuclear-powered cruise missile project (NATO designation *Skyfall*). With the reservation that no reliable facts have been published, expected properties include some similarity in dimensions to the existing Russian Kh-101/Kh-102 air-launched cruise missiles (with a length of 7.45 m and a mass of 2300 kg), very long range, capability to carry a nuclear payload and high manoeuvrability. Various ways of implementing a nuclear power source for a missile engine were discussed – a turbo jet design would be optimal for subsonic speed but would require movable parts and present problems as to how the reactor and control systems would fit. A ramjet design would require a conventional booster to launch and would typically perform optimally at considerably higher speeds, but would offer a simpler design with regard to movable parts. Russia claimed that the *Burevestnik* missile was successfully tested in July 2019, and in August 2019 tests on the White Sea caused some sort of nuclear and radiological emergency including several casualties. There have been no official news during 2020 or 2021.

Source terms. What we need to know on fuel and reactor design (Odd Runevall, SSM)

SSM presented some likely properties of reactor and fuel design for powering a cruise missile. Given a ramjet engine launched to operating speed by a conventional booster, a likely design would be a thermal reactor cooled by the air flow through the engine. The reactor would require some sort of control, possibly based on rotating rods. This would be a high-temperature application, limiting available materials. Ceramic (oxide or possibly nitride) fuel would be likely, possibly in a high-conductivity matrix. A thermal reactor subject to volume and mass constraints would indicate HEU or Pu fuel. For short operating times, such as in a test flight, there would not be appreciable activation product build-up and the fission product inventory in the reactor could be estimated from fission yields given assumptions on operating power and operating time. At the operating temperatures envisaged (1400-1600 °C), fission products would be gaseous. Fission product emissions in an accident would be dependent on the event causing them. If barriers (*i.e.* fuel matrix and some form of reactor containment) were reasonably intact, only volatile fission products would be released to some degree (fission gases, iodine and some of the caesium inventory).

Capabilities of a Reactor Powered Airborne Vehicle (Fredrik Nielsen, FOI)

FOI presented an aerodynamics-based analysis of required reactor power, mass and fuel content given two velocity scenarios: minimum power (*i.e.* maximum flying time), and “effective cruise missile speed”. “Effective speed” (about 900 km/h), vehicle mass (1300 kg in addition to reactor) and aerodynamic properties were taken from the U.S. *Tomahawk* cruise missile. These assumptions resulted, for the minimum power scenario in a velocity of a little over 200 km/h and a required reactor thermal power about 1 MW, and for the effective cruise missile scenario in a required reactor thermal power of slightly under 30 MW.

Summary of the recent NKS-B CRESCENT workshop in Iceland. The Icelandic Perspective (Gísli Jónsson, IRSA)

IRSA summarized the contents of the recent NKS-B CRESCENT workshop, which covered source terms and dispersion modelling, accidents and emergency preparedness, and dose estimates in relation to nuclear-powered sea vessels. While an accident involving a nuclear-powered vessel near Icelandic coasts is the worst-case scenario from the Icelandic perspective, it was also noted that there is a need to be vigilant about the emergence of other potential scenarios, including nuclear-powered flying vehicles. IRSA also mentioned the recent NKS-B NUCSEM seminar on the potential use of nuclear weapons against Nordic countries. IRSA is a small agency with a broad range of responsibilities (everything related to ionizing radiation, including nuclear and radiological emergency preparedness and response). In relation to the scenarios discussed, dispersion modelling and source terms were particularly identified as a capability gap.

Relevant overlaps and lessons from the NKS-B CRESCENT project (Øyvind Gjølme Selnaes, DSA)

DSA presented the scope, background, motivations and findings for the NKS-B CRESCENT project on “credible release scenarios for nuclear-powered vessels operating in Nordic waters”. Factors affecting the analysis to determine a source term were examined, with reference to consequence assessments performed for scenarios related to visits by nuclear-powered vessels to Australian (ARPANSA, 2000) and Norwegian harbours, and the analysis chain from accident scenario via core inventory estimate, release to containment, release to atmosphere and transport in the environment. Previous NKS-B projects investigating the same or related problems were listed, and the need for the CRESCENT project was explained in

terms of increased activity in the High North, new emerging technologies and designs, consolidation and renewal of knowledge and evolving requirements of regulation and emergency planning. Two classes of credible release scenarios were mentioned: reactor-related incidents and outside events having reactor safety consequences. Analysis of accident scenarios in terms of effects on the ship and eventually impact on the reactor was explained, and examples were given of incident and accident scenarios. The need to respond to uncertainty by focussing on factors that have the most effect on the source term was stressed.

Transport modelling – Specification needs (Lennart Robertson, SMHI)

SMHI described the general capabilities of atmospheric transport modelling in describing the fate of compounds in the atmosphere subject to transport and diffusion, sedimentation, deposition and chemical or nuclear transformation. SMHI's MATCH (*Multi scale Atmospheric Transport and Chemistry Model*) was used as an example, developed since 1980 and used for atmospheric chemistry, volcano eruptions and nuclear events. In the example, fallout from a small nuclear explosion was modelled on a 500 m grid, the progression of the radioactive residues illustrated in three spatial dimensions as a function of time from the stabilized cloud immediately following the explosion until the fallout reached the ground.

Assessments and response to the Nyönöksa radiation accident (Mikael Moring, STUK)

STUK summarized the information available on the Nyönöksa accident on August 8, 2019. There were media reports about an explosion on the White Sea and elevated radiation levels (up to 2 micro-Sv/h) measured in the nearby city of Severodvinsk. There were also reports that the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) had measured Sr-91, Ba-139, Ba-140 and La-140 in air filters. STUK noted that these are all decay daughters of short-lived noble gases. At 6 a.m. on the same date there was a reported seismic event of magnitude 2.8 at a location on the White Sea about 30 km from Severodvinsk and approximately 400 km from Finland. There were no detections of man-made radioactivity in the Finnish air filter network, nor any elevated radiation levels detected in the Finnish dose rate network. Atmospheric transport modelling showed air masses moving south east at the time, away from Finnish borders. Based on dose rates reported from Severodvinsk, STUK estimates the magnitude of a release from the site of the seismic event to have been in the range of 10-100 TBq.

Short briefs on assessments performed

SSM (Anders Axelsson) presented the assessment done by SSM relating to media reporting on possible *Burevestnik* flight test preparations at a site in Novaya Zemlya (about 1200 km from Sweden) in August 2021. The assessment was based on a short (10 minutes) flight with a reactor thermal power of 1 MW and resulted in a core inventory of about 2000 TBq (referenced to 60 minutes after shut-down). Even assuming the (unlikely) complete aerosolization of the core by fire or explosion in the course of an accident, a release of this magnitude would be very unlikely to lead to radiation protection consequences in Sweden. The radiation situation at or near the site of a crash, could however pose serious health risks from large pieces, fragments or dispersed particles from the core.

STUK (Mikael Moring) stated, as part of the presentation summarized above on the Nyönöksa accident of 2019, that the assessment at the time of that accident was that there was no dangerous radioactivity levels possible in Finland due to the large distance (about 400 km).

Discussions aimed at outlining conclusions and report contents (all)

See separate section on the workshop discussions.

5. Workshop discussions

Discussions prompted by the presentations or points developed from questions and discussions have been organized separately in this section. The thematic arrangement is somewhat arbitrary but follows to some degree the possible “entry points” to discussing the subject matter of the workshop that were identified in the planning of the workshop and given in the introduction.

5.1 General considerations

The fundamental difficulty in analysing the problem of possible release scenarios from reactor-powered flying vehicles is that very little is known on which to base any analyses.

Clearly, the assumptions that need to be made about the reactor used greatly impact assessments of possible accident scenarios and radiation risks. Source term estimates require a core inventory, which requires a reactor power. Estimating a source term also requires estimating what fraction of the core inventory is released, and in what form. This requires assumptions on the fuel, the fuel matrix and possible other barriers to release.

Furthermore, assumptions are required on flight and flight testing parameters in order to arrive at reasonable operating times and the nature of potential risks involved (e.g. what are realistic accident scenarios, and what fire and explosion risks are involved?).

Ultimately, most such factors require assumptions on the requirements the vehicle is designed to fulfil. Very little is known, as noted in several of the presentations made. Presumably a reactor-powered missile is developed in order to provide a long flying time, whether this is used to achieve a long range or a long loiter time in a target area or decreased first-strike vulnerability by remaining airborne over friendly territory before a mission is initiated, or some combination of such capabilities. Open source reviews referenced by the workshop indeed indicate this: the purpose of the *Burevestnik* is to “evade missile defence, follow untraditional flight paths, and be able to strike any target with little warning” (Hruby, 2019). Russian president Putin also stressed these capabilities in his 2018 speech (Wolf, 2020).

It is also assumed that a nuclear-powered missile would be designed to carry a nuclear payload, although this aspect was not the focus of the NUPFLIGHT workshop. The *Burevestnik* system appears designed primarily to provide a strategic second-strike capability, and would not be required in order to strike the Nordic countries. Therefore, the NUPFLIGHT workshop focused on radiation risks related to testing, including test flights, of the nuclear-powered delivery vehicle.

5.2 Reactor properties

Reports of early U.S. research projects concerning reactors used to power flying vehicles were referenced during the meeting discussions (Hadley, 1959 and Walter, 1964). The FFI presentation (see summary in previous section) also made reference to the *Pluto* project, which reportedly suffered from problems related to radioactive contamination and noise. The project aimed at a supersonic missile capable of carrying a “large thermonuclear warhead” in Mach 3 flight at some hundreds of meters altitude (1000 feet), and with a flying time of 3 to 10 hours. The reactor used, Tory II-C, was designed for 500 MW thermal power, was tested on a railway cart, and featured ceramic fuel pins operating at a temperature of about 1400 °C.

FOI's aerodynamics-based analysis was seen as a fruitful way to somewhat constrain assumptions that need to be made about reactor power and fuel contents. However, the two scenarios presented as examples were based on quite different mission requirements ("maximum flight time" and "*Tomahawk* cruise missile speed"), and lead to very different thermal power requirements (about 1 MW and about 30 MW, respectively). While the latter scenario was deemed more likely (being based on how an existing cruise missile operates), the discrepancy illustrates the sensitivity to assumptions made. It was noted that for a HEU-fuelled reactor, the specific-power assumption used in the analysis might be raised considerably. This results in a correspondingly lower core and reactor mass, lower total missile mass and ultimately in a lower thermal power requirement. FOI's estimate for thermal power required for the "cruise missile speed" scenario using a specific power more typical for HEU fuel is 6-9 MW.

Other points that were raised in the discussions related to reactor and fuel properties were the potential effects on shielding and containment of severe weight limitations in the design, and the possibility that fuel designed to tolerate very-high-temperature operation might limit the potential for release of fission products in the event of an accident.

5.3 Scenarios

One way to structure the problem is to evaluate specific situations or scenarios, an approach that is used to advantage in the NKS-B CRESCENT project on reactors at sea (see summaries of the DSA and IRSA presentations). At the present state of knowledge, with very little information to constrain any analysis, it is difficult to go further than identifying some basic situations or scenarios and some possible basic implications. The workshop discussions along these lines are summarized here, since they may help guide future studies or modelling attempts or even responses to reported incidents where even a small amount of specific information is available (*e.g.* what questions to ask, or what calculations or measurements to attempt).

There may be reasons, perhaps especially for more detailed risk assessments, to distinguish between incidents with the reactor itself and incidents with some other system that will affect the reactor.

An accident at launch, after no or quite short reactor operation time, could mean that the reactor contained a very small inventory of radioactive materials, possibly only the fuel itself (which might still present some local hazard especially if Pu-based). A short operating time before an accident might also mean that the fuel, and the fission products in particular, had not yet reached the high temperatures expected to apply at stable operating conditions. This could in turn influence the fraction of the core inventory that is released following an accident.

An accident during stable reactor operation (at high temperature) could mean that a larger fraction of the core inventory is more easily released, since the fission products will be at temperatures above their boiling points. Operating time also affects the size and composition of the core inventory. At the start of operation, activity increases rapidly. As time goes by, more nuclides will reach their equilibrium activity for a given neutron flux, and increase of total activity is progressively slower. However, long-lived nuclides, which typically cause more concern from an emergency preparedness and response point of view, reach equilibrium later. That is, the total activity increases more slowly with time, but it will consist of an increasing fraction of longer-lived nuclides. The size and composition of the core inventory is

easily modelled (at least to the fidelity required for emergency preparedness) for any given power level and operating time, but is highly dependent on both of these input quantities.

The risk of fire or explosion will impact considerations of the fraction of the core inventory that is released for long-range dispersion. If the vehicle is launched using a conventional rocket engine, there will be sizeable quantities of rocket fuel available to cause fire or explosion. One potential type of engine implementing a nuclear reactor could be a *nuclear thermal rocket* (NTR) using liquid hydrogen as reaction mass. If this type of engine is used, liquid hydrogen would be available to cause fire or explosion on board during the entire flight.

Both for risk assessments and in terms of modelling tools, a scenario where radioactive debris is released in aerosol form and dispersed at large distances should be distinguished from a scenario where large or small pieces, fragments and particles are scattered at a crash site or along a final flight trajectory. Both of these scenarios could occur in various degrees as the result of an accident. For the former, a modelling tool such as SMHI's MATCH (see presentation summarized above) and dose prognosis such as calculated by the ARGOS nuclear decision support system for emergency management organizations (Hoe *et. al.*, 2009) would be appropriate. For the latter, tools such as HotSpot (Homann and Aluzzi, 2014) may be useful.

Regular operation radiation levels and radioactive emissions caused in the absence of an abnormal event could also be considered. Likely emissions from the various fuel, reactor and engine concepts discussed could be of interest for further study. Likewise, doses due to direct radiation from a small reactor, presumably with comparatively little shielding, during a fly-by at distances corresponding to assumed cruise missile flying altitudes, could be modelled.

A crash into the sea, leaving a reactor intact, or damaged to some degree, exposed to the environment could be considered in terms of a longer-time scale environmental and health risk as components fail due to corrosion *etc.* In this regard, the possibility of a criticality situation as a missile-propulsion reactor comes contact with sea water in the course of an uncontrolled situation could also be considered, although possible landing in the sea would presumably be considered in the design of a missile engine.

5.4 Possible parallels and comparisons

Considering a problem where very little is known, discussions at the workshop attempted to find some solid ground and obtain some guidance from more well-known concepts.

Although in many ways expected to be very different, there are also some useful parallels between reactors used to power flying vehicles and maritime propulsion reactors. For example, they are both exposed to risks that nuclear power plants or other reactors on land are not. Also, risk assessments and other analyses that have been done for nuclear-powered sea vessels can be re-examined and perhaps to some degree scaled in light of differences compared to flying vehicles – such as power, design concepts, temperatures and amount of shielding and confinement available.

Several assumptions that need to be made in any hazard assessment depend on factors related to how a testing programme for a nuclear-powered cruise missile would be designed. One example is what flight times and distances would be useful from a technical point of view, and what other factors would possibly constrain them. Another example is what arrangements

would be made for recovery of the missile and the reactor after a test flight. Some such considerations could be informed by corresponding details of other testing programmes, perhaps for conventional cruise missiles.

There are possible parallels between some potential reactor-powered missile testing accident scenarios and accident scenarios with nuclear-powered satellites. In-flight break-down and fragmentation might lead to distribution of large and small radioactive core and structural fragments over an extended area. In this respect, there may be some similarities to an event like the crash of a Soviet nuclear-powered radar ocean reconnaissance satellite in Canada in 1978 (Gummer *et. al.*, 1980). However, it should be noted that there are also very significant differences between a cruise missile and a re-entering satellite. For example, the expected flying altitude of a cruise missile is low, perhaps well below 100 m, and it is assumed that the *Burevestnik* is a subsonic vehicle.

5.5 Possible questions from the public and from policy-makers

The workshop spent some time considering what questions might need to be answered in the event of incidents involving reactor-powered flying vehicles. The discussion was also informed by recent experiences with public concerns with potential nuclear and radiological hazards related to the war in Ukraine. Generally, the participants did not strive to formulate actual answers for recording in this report, since specific contents of official communication with the public would be out of scope for this project. In terms of points that might need to be addressed, here are a few examples:

- Individuals that have been or believe they have been exposed to released radioactive material in the neighbourhood of an accident site
- Radiological consequences of an accident on site versus consequences at regional or continental distances
- Should iodine thyroid blocking be applied?
- Comparison to a nuclear power plant accident
- Comparison to a "dirty bomb"
- Comparison to a crashing satellite (during launch or after re-entry)
- Comparison to a nuclear weapon
- Distinguishing between a flying reactor and its intended (presumably nuclear) payload
- Distinguishing between a test flight and intended wartime use
- Operational emissions versus potential consequences of an accident
- Direct radiation from the reactor versus release of radioactive materials
- The difference between detectable levels and radiologically hazardous levels of radioactive materials in long-distance dispersion

6. Conclusions

For Nordic authorities responsible for emergency preparedness and response to nuclear and radiological emergencies, it is useful to "compare notes" and jointly examine and discuss assumptions and approaches, particularly for a problem with very few solid facts available.

It was remarked by participants that the workshop was interesting and provided a lot of food for thought. In any discussions going further, more expertise in cruise missile technology, including development and testing would clearly be beneficial, as would additional consideration from arms control and weapons of mass destruction experts (given the dependencies on assumed purpose, mission and design requirements).

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that considerations of general principles such as power requirements, flight times, temperatures, weight and the properties of conceivable fuel materials and designs could be used to bound the problem and assist in improving the confidence in risk assessments.

This report summarizes the NUPFLIGHT workshop and also reflects post-workshop comments and refinements.

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