ANALYSIS OF ALTERNATIVES

and

SOCIO-ECONOMIC ANALYSIS

Complete version

Legal name of applicant(s):	Boeing Distribution (UK) Inc. Henkel Ltd MacDermid Performance Solutions UK Ltd Wesco Aircraft EMEA Ltd
Submitted by:	Boeing Distribution (UK) Inc. on behalf of the Aerospace and Defence Chromates Reauthorisation Consortium
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Substance:	Chromium trioxide (includes “Acids generated from chromium trioxide and their oligomers”, when used in aqueous solutions)
Use title:	Electroplating using chromium trioxide in aerospace and defence industry and its supply chains
Use number:	1

Note

This submission includes no confidential information declared in this document. All information contained in this document can be made public. There is no accompanying document which provides confidential information, as a result there are no justifications for claiming any information confidential.

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Abbreviations

ADCR – Aerospace and Defence Chromates Reauthorisation

A&D – Aerospace and Defence

AfA – Application for Authorisation

AoA – Analysis of Alternatives

AoG – Aircraft on the Ground

BCR – Benefit to Cost Ratio

BtP – Build-to-Print manufacturer

CCST – Chromium VI Compounds for Surface Treatment

CMR – Carcinogen, Mutagen or toxic for Reproduction

Cr(VI) – hexavalent chromium

CSR – Chemical Safety Report

CT – Chromium trioxide

CTAC – Chromium Trioxide Authorisation Consortium

DtB – Design-to-Build manufacturer

DtC – Dichromium tris(chromate)

EASA - European Aviation Safety Agency

EBITDA - Earnings before interest, taxes, depreciation, and amortization

ECHA – European Chemicals Agency

EEA – European Economic Area

ESA – European Space Agency

GCCA – Global Chromates Consortium for Authorisation

GDP – Gross domestic product

GOS – Gross operating surplus

ICAO – International Civil Aviation Organisation

MoD – Ministry of Defence

MRL – Manufacturing readiness level

MRO – Maintenance, Repair and Overhaul

NADCAP - National Aerospace and Defence Contractors Accreditation Program

NATO – North Atlantic Treaty Organisation

NUS – Non-use scenario

OELV – Occupational Exposure Limit Value

OEM – Original Equipment Manufacturer

RAC – Risk Assessment Committee

REACH - Registration, Evaluation, Authorisation and restriction of Chemicals

RR - Review Report

SC – Sodium chromate

SD – Sodium dichromate

SEA – Socio Economic Analysis

SEAC – Socio Economic Analysis Committee

SME – Small and medium-sized enterprises

SVHC – Substance of Very High Concern

T&E – Testing and Evaluation

TRL – Technology readiness level

UK – United Kingdom

WCS – Worker contributing scenario

Glossary

Term	Description
Active Corrosion Inhibition	The ability of a corrosion protection system to spontaneously repair small amounts of chemical or mechanical damage that exposes areas of metal without any surface protection (“self-healing properties”). Active corrosion inhibition can be provided by soluble corrosion inhibitors.
Adhesion promotion	The ability of the treatment to improve and maintain the adhesion of subsequent layers such as paints, primers, adhesives, and sealants. It also includes the adhesion of the coating to the substrate.
Aeroderivative	Parts used in power generation turbines used to generate electricity or propulsion in civil and defence marine and industrial applications that are adapted from the design/manufacturing processes and supply chains that produce parts for the aerospace industry. Typical applications include utility and power plants, mobile power units, oil and gas platforms and pipelines, floating production vessels, and for powering marine/offshore vessels such as Naval warships.
Aerospace	Comprises the civil and military aviation, and space industries.
Aerospace and Defence (A&D)	Comprises the civil and military aviation, space industries and the public organisations and commercial industry involved in designing, producing, maintaining, or using military material for land, naval or aerospace use.
Aircraft	A vehicle or machine able to fly by gaining support from the air. Includes both fixed-wing and rotorcraft (e.g. helicopters).
Airworthiness	Airworthiness is defined by the International Civil Aviation Organisation as "The status of an aircraft, engine, propeller or part when it conforms to its approved design and is in a condition for safe operation". Airworthiness is demonstrated by a certificate of airworthiness issued by the civil aviation authority in the state in which the aircraft is registered, and continuing airworthiness is achieved by performing the required maintenance actions.
Airworthiness Authority	The body that sets airworthiness regulations and certifies materials, hardware, and processes against them. This may be for example the European Union Aviation Safety Authority (EASA), the Federal Aviation Administration (FAA), or national defence airworthiness authorities.
Airworthiness regulations	Set performance requirements to be met. The regulations are both set and assessed by the relevant airworthiness authority (such as EASA or national Ministry of Defence (MoD) or Defence Airworthiness Authority).
Alternative	Test candidates which have been validated and certified as part of the substitution process.
Assembly	Several components or subassemblies of hardware which are fitted together to make an identifiable unit or article capable of disassembly such as equipment, a machine, or an Aerospace and Defence (A&D) product.
Aviation	The activities associated with designing, producing, maintaining, or flying aircraft.
Benefit-Cost Ratio (BCR)	An indicator showing the relationship between the relative costs and benefits of a proposed activity. If an activity has a BCR greater than 1.0, then it is expected to deliver a positive net present value.
Build-to-Print (BtP)	Companies that undertake specific processes, dictated by the OEM, to build A&D components.
Certification	The procedure by which a party (Authorities or MOD/Space customer) gives written assurance that all components, equipment, hardware, services, or processes have

Term	Description
	satisfied the specific requirements. These are usually defined in the Certification requirements.
Coefficient of friction	Friction is the force resisting the relative motion of solid surfaces sliding against each other. The coefficient of friction is the ratio of the resisting force to the force pressing the surfaces together.
Component	Any article regardless of size that is uniquely identified and qualified and is either included in a complex object (e.g. frames, brackets, fasteners and panels), or is a complex object itself (e.g. an assembly or sub-system)
Compound annual growth rate	The mean annual growth rate of an investment over a specified period of time, longer than one year.
Corrosion protection	Means applied to the metal surface to prevent or interrupt chemical reactions (e.g. oxidation) on the surface of the metal part leading to loss of material. The corrosion protection provides corrosion resistance to the surface.
Defence	Comprises the public organisations and commercial industry involved in designing, producing, maintaining, or using military material for land, naval or aerospace use.
Design	A set of information that defines the characteristics of a component (adapted from EN 13701:2001).
Design owner	The owner of the component/assembly/product detailed design. For Build-to-Print designs, the design owner is usually the OEM or military/space customer. For Design-to-Build, the supplier is the design owner of the specific hardware, based on the high-level requirements set by the OEM (as their principal).
Design-to-Build (DtB)	Companies which design and build components. Also known as “Build-to-Spec".
Embrittlement	The process of becoming degraded, for example loss of ductility and reduction in load-bearing capability, due to exposure to certain environments.
Fatigue	Progressive localised and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at stresses less than the tensile strength of the material. The “permanent structural change” is in the form of microcracks in the crystal structure that can progressively lead to potentially catastrophic macro-cracking and component failure.
Flexibility	The ability to bend easily without breaking or permanently deforming.
Formulation	A mixture of specific substances, in specific concentrations, in a specific form.
Formulator	Company that manufactures formulations (may also design and develop formulations).
Gross Domestic Product (GDP)	The standard measure of the value added created through the production of goods and services in a country during a certain period. As such, it also measures the income earned from that production, or the total amount spent on final goods and services (less imports).
Gross Operating Surplus	Equivalent to economic rent or value of capital services flows or benefit from the asset.
Gross Value Added	The value of output less the value of intermediate consumption; it is a measure of the contribution to GDP made by an individual producer, industry or sector.
Hardness	Ability of a material to withstand localized permanent deformation, typically by indentation. Hardness may also be used to describe a material’s resistance to deformation due to other actions, such as cutting, abrasion, penetration and scratching.
Heat resilience	The ability of a coating or substrate to withstand repeated cycles of heating and cooling and exposure to corrosive conditions. Also known as cyclic heat-corrosion resistance.
Hot corrosion resistance	The ability of a coating or substrate to withstand attack by molten salts at temperatures in excess of 400°C.

Term	Description
Industrialisation	The final step of the substitution process, following Certification. After having passed qualification, validation and certification, the next step is to industrialise the qualified material or process in all relevant activities and operations of production, maintenance, and the supply chain. Industrialisation may also be referred to as implementation.
Layer thickness	The thickness of a layer or coatings on a substrate.
Legacy parts	Any part that is already designed, validated, and certified by Airworthiness Authorities or for defence and space, or any part with an approved design in accordance with a defence or space development contract. This includes any part in service.
Material	The lowest level in the system hierarchy. Includes such items as metals, chemicals, and formulations (e.g. paints).
Maintenance, Repair and Overhaul (MRO)	The service of civilian and/or military in-service products. Term may be used to describe both the activities themselves and the organisation that performs them.
NACE	The Statistical Classification of Economic Activities in the European Community. It is part of the international integrated system of economic classifications, based on classifications of the UN Statistical Commission (UNSTAT), Eurostat as well as national classifications.
NADCAP	National Aerospace and Defence Contractors Accreditation Program which qualifies suppliers and undertakes ISO audits of their processes.
Net Present Value	Valuation method to value stocks of natural resources. It is obtained by discounting future flows of economic benefits to the present period.
Original Equipment Manufacturer (OEM)	Generally large companies which design, manufacture, assemble and sell engines, aircraft, space, and defence equipment (including spare parts) to the final customer. In addition, an OEM may perform MRO activities.
Part	Any article or complex object.
Pickling	The removal of surface oxides and small amounts of substrate surface by chemical or electrochemical action.
Present Value	The discounted sum of all future debt service at a given rate of interest. If the rate of interest is the contractual rate of the debt, by construction, the present value equals the nominal value, whereas if the rate of interest is the market interest rate, then the present value equals the market value of the debt.
Pre-treatment	Pre-treatment processes are used, prior to a subsequent finishing treatment (e.g. chemical conversion coating, anodising), to remove contaminants (e.g. oil, grease, dust), oxides, scale, and previously applied coatings. The pre-treatment process must also provide chemically active surfaces for the subsequent treatment. Pre-treatment of metallic substrates typically consists of cleaning and/or surface preparation processes.
Producer surplus	Represents the gain to trade a producer receives from the supply of goods or services less the cost of producing the output (i.e. the margin on additional sales).
Proposed candidate	A formulation in development or developed by a formulator as a part of the substitution process for which testing by the design owner is yet to be determined. In the parent applications for authorisation, this was referred to as a 'potential alternative'.
Qualification	1. Part of the substitution process following Development and preceding Validation to perform screening tests of test candidate(s) before determining if further validation testing is warranted 2. The term qualification is also used during the industrialisation phase to describe the approval of suppliers to carry out suitable processes.
Requirement	A property that materials, components, equipment, or processes must fulfil, or actions that suppliers must undertake.

Term	Description
Resistivity	Property that quantifies how a given material opposes the flow of electric current. Resistivity is the inverse of conductivity.
Social Cost	All relevant impacts which may affect workers, consumers and the general public and are not covered under health, environmental or economic impacts (e.g. employment, working conditions, job satisfaction, education of workers and social security).
Specification	Document stating formal set of requirements for activities (e.g. procedure document, process specification and test specification), components, or products (e.g. product specification, performance specification and drawing).
Standard	A document issued by an organisation or professional body that sets out norms for technical methods, processes, materials, components, and practices.
Sub-system	The second highest level in the system hierarchy. Includes such items as fuselage, wings, actuators, landing gears, rocket motors, transmissions, and blades.
Surface morphology	The defined surface texture of the substrate.
System	The highest level in the system hierarchy. Includes such items as the airframe, gearboxes, rotor, propulsion system, electrical system, avionic system, and hydraulic system.
System hierarchy	The grouping/categorisation of the physical elements that comprise a final product (such as an aircraft), according to their complexity and degree of interconnectedness. Comprises materials, components, assemblies, sub-systems, and systems.
Temperature resistance	The ability to withstand temperature changes and extremes of temperature.
Test candidate	Materials which have been accepted for testing or are currently undergoing testing by a design owner, as a part of the substitution process. In the parent applications for authorisation, this was referred to as a 'candidate alternative'.
Type certificate	Document issued by an Airworthiness Authority certifying that an Aerospace product of a specific design and construction meets the appropriate airworthiness requirements.
Validation	Part of the substitution process following Qualification and preceding Certification, to verify that all materials, components, equipment, or processes meet or exceed the defined performance requirements.
Value of statistical life	Values the impact of risks to the length of life.
Verification	The process of establishing and confirming compliance with relevant procedures and requirements.
Wear resistance	The ability of a surface to withstand degradation or loss due to frictional movement against other surfaces.
Sources: GCCA and ADCR consortia	

DECLARATION

We, the Applicants, are aware of the fact that further evidence might be requested by HSE to support the information provided in this document.

Also, we request that the information blanked out in the "public version" of the Analysis of Alternatives and Socio-economic Analysis is not disclosed. We hereby declare that, to the best of our knowledge as of today 11 November 2022, the information is not publicly available, and, in accordance with the due measures of protection that we have implemented, a member of the public should not be able to obtain access to this information without our consent or that of the third party whose commercial interests are at stake.

Signature: Date: 11 November 2022

Sr. Chemical Policy Analyst
The Boeing Company

1 Summary

This combined AoA/SEA uses some terms in a manner specific to the aerospace and defence sector. Please see the glossary for explanations of the specific meaning of commonly used words, such as component, and other technical terms within the context of this report.

1.1 Introduction

The Aerospace and Defence Chromates Reauthorisation (ADCR) Consortium on behalf of the applicants has developed several review reports and new applications. These review reports or new applications cover all uses of soluble chromates considered to be relevant by the ADCR consortium members. Although formally they are upstream applications submitted by manufacturers, importers or formulators of chromate-containing chemical products, the applications are based on sector-specific data and detailed information obtained from actors throughout the supply chain.

For the purposes of this document, the term 'aerospace and defence' comprises the civil aviation, defence/security and space industries, as well as aeroderivative products. The aerospace and defence (A&D) industry has been working towards the substitution of Cr(VI) across various uses for the past 25-30 years. Although there have been numerous successes and levels of use have decreased significantly, the specific use of hexavalent chromium compounds in electroplating[1] is still required for many products. This remains critical to both flight safety and to military mission readiness, and hence to society. The socio-economic impacts of a refused authorisation are therefore significant not just for the sector but also for the EEA and UK societies and economies more generally. Furthermore, at the EU level, the A&D sector is one of the 14 sectors highlighted by the EU's New Industrial Strategy[2] as being important to innovation, competition and a strong and well-functioning single market.

The parent authorisations to this review report were specific to the use of chromium trioxide in electroplating, also referred to as hard chrome plating. The definition of the use is therefore the same as that adopted by the original Chromium Trioxide Authorisation Consortium (CTAC). Other surface treatments are also being supported by the ADCR, and these are covered by separate, complementary submissions for each "use".

The specific use covered by this combined AoA/SEA is defined as:

1) Electroplating using chromium trioxide in aerospace and defence industry and its supply chains.

The "applied for use" involves the continued use of chromium trioxide across the EEA and the UK for a further 12-year review period. This includes use at approximately 125 sites in the EU and 25 sites in

[1] Review Reports are also being submitted by the ADCR covering ten other uses of the chromates in formulation and other specific surface treatment activities as more narrowly defined by the ADCR.

[2] https://op.europa.eu/en/publication-detail/-/publication/52904a0b-ae95-11eb-9767-01aa75ed71a1/language-en

the UK, involved in the production of components and end products, as well as maintenance, repair and overhaul services for both civil aviation and military bodies, as well as aeroderivative uses.

It is estimated that these sites in the EEA and UK consume between 0.3 to 40 tonnes per site per annum. This range is based on the maximum consumption per site identified from the CSR, Article 66 notifications and the percentage of sites using chromium trioxide as identified in responses to the SEA questionnaire and from discussions with formulators and distributors. Some sites could consume less but 40 tonnes is considered to be the maximum and atypical.

1.2 Availability and suitability of alternatives

For the past several decades, ADCR members who are "design owners" (including Original Equipment Manufacturers (OEMs) and Design-to-Build (DtB) manufacturers) for products used in civil aviation and military aircraft, ground and sea-based defence systems, and aeroderivatives have been searching for alternatives to the use of chromium trioxide in electroplating for the manufacture and MRO of affected products and components. At the current time, the remaining instances of hard chrome plating form a portion of an overall system providing the following key functions:

- Abrasion/wear resistance;
- Corrosion Resistance;
- Hardness;
- Tribological properties (reduced friction);
- Layer thickness; and
- Effect on surface morphology (Flexibility to coat/treat complex geometries).

Electroplating involves submerging the substrate in an electrolytic plating solution to impart a hard, wear resistant coating. The process is usually combined with pre-treatments, such as degreasing and etching, and post-treatments (e.g. impregnation with resins or primers, or thermal treatment for hydrogen de-embrittlement). The coating can be removed with either mechanical or Cr(VI) free processes.

OEMs (as design owners), in particular, have responsibility for certification of components using alternatives and have conducted a full analysis of their requirements into the future, taking into account progress of R&D, testing, qualification, certification and industrialization activities. The companies are at different stages in the implementation of alternatives. One of the key complexities is the need for varying alternatives depending on components and final product. As a result some OEMs expect to be able to substitute chromium trioxide in electroplating across some of their current components, final products and MRO (maintenance, repair and overhaul) processes within the next four to seven years; while others have not yet been able to identify technically feasible alternatives for all components and final products and MRO processes that meet performance requirements, and will require a further 12 years to develop, gain certifications for and then implement a test candidate. A further set are constrained by military and MRO requirements which may mean that it will take at least 12 years to implement technically feasible substitutes.

Furthermore, obtaining such certification across hundreds of components is a time-consuming and costly process, given the strict testing regimes that must be adhered to achieve the qualification, validation and certification of components using an alternative. At the sectoral level, therefore, and to ensure minimisation of supply chain disruption and associated business risks, a 12-year review period is requested. Business risks arise from the need for alternatives to be available and deployed across all components and suppliers to ensure continuity of manufacturing activities across the supply chain. A shorter period would impact on the functioning of the current market, given the complexity of supply chain relationships.

Companies engaged in maintenance, repair and overhaul (MRO) activities face particular substitution difficulties, as they are mandated to continue use of chromium trioxide in electroplating if this is specified in the Maintenance Manuals provided to them by the OEMs. MROs (military and civilian) are legally obliged to carry out their activities in line with the requirements set out in Maintenance Manuals, given the importance of these to ensuring airworthiness and the safety and reliability of final products. As a result, they rely on the completion of the R&D, testing and certification activities of the OEMs and the update of the Maintenance Manuals, before they are able to adopt alternative substances or processes.

As a result of the different requirements outlined above, at the sectoral level, there will be an on-going progression of substitution over the requested 12-year review period (see Section 3.7.2 and **Figure 1-1** below). The potential need for more than 12 years has been identified by multiple OEMs due to their failure to identify any technically and economically feasible alternatives to date, or due to the need by MROs and MoDs for continued use in the maintenance and repair of in-service (legacy) final A&D products.

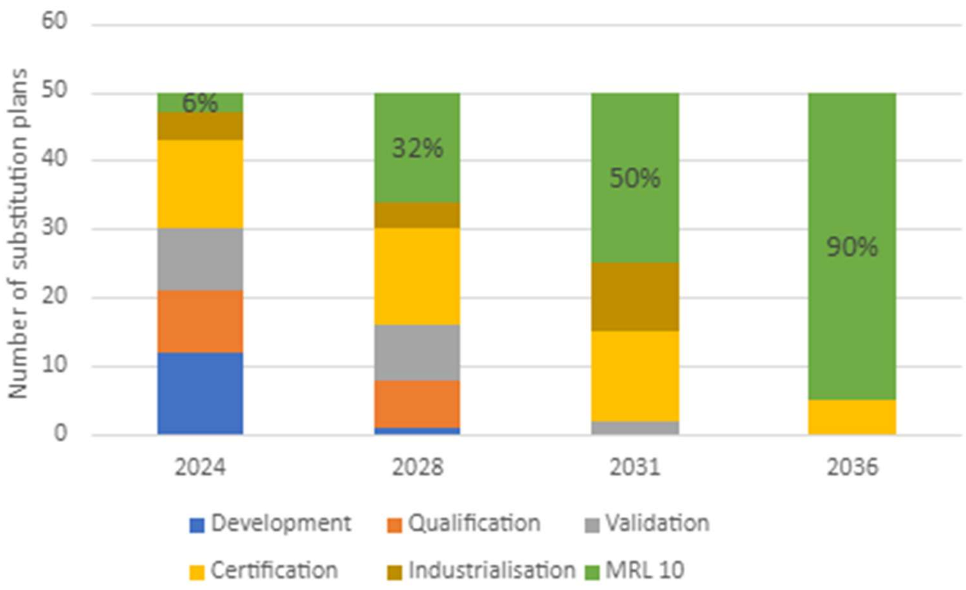

Figure 1-1: Expected progression of substitution plans for the use of Cr(VI) in electroplating, by year
The vertical axis refers to number of substitution plans (some members have multiple substitution plans for electroplating). The percentage value shown on each of the green bars indicates the proportion of substitution plans that are expected to have reached MRL 10 by the date indicated. MRL 10 is the stage at which there is expected to be a significant reduction in Cr(VI) usage.
***Source:* RPA analysis, ADCR members**

1.3 Socio-economic benefits from continued use

The continued use of chromium trioxide in electroplating specifically (ADCR Use #1) over the review period will confer significant socio-economic benefits to ADCR members, their suppliers and to their end customers which include civil aviation, the military, space and emergency services. It will also ensure the continued functioning of the aerospace and defence supply chains in the EEA and UK, conferring the wider economic growth and employment benefits that come with this.

The benefits can be summarised as follows (with the detailed calculations set out in Section 5):

- Importers of the chromium trioxide used in electroplating will continue to earn low levels of profits from sales to the aerospace and defence sector;

- OEMs will be able to rely on the use of chromium trioxide in electroplating by their EEA and UK suppliers and in their own production activities. The avoided profit losses to these companies under the continued use scenario would equate to between €641 to €3,403 million for the EEA and €175 to €1,386 million for the UK in present value terms over a two-year period, as well as being able to maintain their subsequent manufacturing activities in both jurisdictions. These figures exclude the potential profits that could be gained under the continued use scenario from the global increase in demand for A&D final products;

- Build-to-Print (BtP) and Design-to-Build (DtB) suppliers would be able to continue their production activities and meet the performance requirements of the OEMs. The associated profit losses that would be avoided under the continued use scenario for these companies are calculated at €90 to €900 million for the EEA and €123 - €161 million for the UK in present value terms over a two-year period;

- Under the non-use scenario MRO companies which provide maintenance and repair services to both civil aviation and/or military forces, would be forced to move some operations outside the EEA/UK, with the consequent profit losses equating to between €87 – €1,340 million for the EEA and between €5 - €1,225 million for the UK in present value terms over a two-year period;

- Continued high levels of employment in the sector, with these ensuring the retention of highly skilled workers paid at above average wage levels. From a social perspective, the benefits from avoiding the unemployment of workers involved in electroplating alone and linked surface treatment and manufacturing activities are estimated at €2,800 million for the EEA and €760 million in the UK. The losses vary significantly across the different EEA countries, with France incurring the highest social costs of unemployment, followed by Germany and Italy.

- Critically civil aviation, emergency services and the military will benefit from the continued flight safety and mission readiness of aircraft and other equipment;

- Military forces will be able to repair and maintain existing aircraft and other equipment to ensure operational readiness and the ability to respond to missions as required; and

- The general public will benefit from continued safe flights, fewer flight delays, the on-time delivery of cargo and goods, and the economic growth provided by the contributions of these sectors to the economic development, as well as R&D and technological innovation, while alternatives are qualified, certified and industrialised.

It is clear that the level of disruption that would be caused through the inability to continue electroplating activities to A&D customers and society would outweigh the losses to the A&D companies and their supply chains (including OEMs, BtP and DtB suppliers, MROs and MoDs).

1.4 Residual risk to human health from continued use

The parent authorisations placed conditions on the continued use of chromium trioxide in surface treatments, including in electroplating. The A&D sector has made huge efforts to be compliant with these conditions, investing not only in risk management measures but also improved worker and environmental monitoring. Significant technical achievements also have been made in developing and qualifying alternatives for use on some components/final products, although there remain technical challenges for other components and final products. As a result, it is projected that from 2024 based on current company specific substitution plans, where technically and economically feasible, consumption of chromium trioxide by ADCR members and their suppliers will decline significantly over the requested 12-year review period.

For the purposes of the human health risk assessment, however, it has been assumed that the quantities used and the number of sites using chromium trioxide remains constant over the 12-year period. This will lead to an overestimate of the residual risks to both workers and humans via the environment.

Risks to workers have been estimated based on the use of exposure monitoring data, supplemented by modelling data as appropriate. Across the 125 EEA sites where electroplating is anticipated as taking place, an estimated total of 2,500 workers may be exposed to Cr(VI); for the 25 UK sites where electroplating takes place, approximately 500 workers may be exposed.

Exposures for humans via the environment have been calculated for the local level only. Based on the population density of the different countries within which electroplating is considered to take place, an estimated 66,000 people in the EEA and around 33,000 people in the UK[3] are calculated as potentially being exposed to Cr(VI) due to electroplating activities.

The predicted number of cancer cases per annum and the annualised economic value of these social costs for both workers and humans via the environment are[4]:

- EEA: 0.2 fatal cancers and 0.05.non-fatal cancers per annum at a total social cost of €800,078 per annum;

- UK: 0.07 fatal cancers and 0.02 non-fatal cancers per annum at a total social cost of €287,570 per annum.

1.5 Comparison of socio-economic benefits and residual risks

The ratio of the benefits of continued use to the total residual risks to human health are as follows for the EEA and UK respectively (based on two years for economic losses and 12 years for health risks @ 4%):

- EEA: 2,061 : 1 for the lower bound of economic losses or 3,636 : 1 for the upper bound economic losses;

[3] Although the number of people exposed under the local scenario appears disproportionate for the UK compared to the EU population exposed, this is due to the UK's high population density.

[4] Discounted over 12 years at 4% per annum, and assuming a 20 year lag in effects.

- UK: 1,465 : 1 for the lower bound of economic losses or 2,897 : 1 for the upper bound economic losses.

The above estimates represent a significant underestimate of the actual benefits conferred by the continued use of chromium trioxide in electroplating, as it only encompasses benefits that could be readily quantified and monetised. The true benefit-cost ratios must be assumed to also encompass:

- The significant benefits to civil aviation and military customers, in terms of flight readiness and military preparedness of aircraft and equipment;

- The avoided impacts on air transport – both passenger and cargo – across the EEA and the UK due to stranded aircraft on the ground (AoG), reductions in available aircraft, increased cost of flight for passengers, or cargo ships, etc.;

- The avoided impacts on society more generally due to impacts on air transport and the wider economic effects of the high levels of unemployment within a skilled workforce, combined with the indirect and induced effect from the loss of portions of the A&D sector from the EEA and UK as they either cease some activities or relocate relevant operations; and

- Avoided economic and environmental costs associated with increased transporting of components in and out of the EEA/UK for maintenance, repair and overhaul (whether civilian or military) and production activities.

1.6 Factors to be considered when defining the operating conditions, risk management measures, and/or monitoring arrangements

A range of factors should be taken into account when considering the need for additional risk management measures and/or monitoring requirements:

- The sector has reduced the volume of Cr(VI) used in electroplating activities, with chromium trioxide now the only relevant chromate and the estimated volumes of chromium trioxide used in the EEA being a maximum of around 500 tonnes per annum (and expected to be significantly less), and a maximum in the UK of around 100 tonnes per annum.

- Occupational exposure monitoring requirements were placed on downstream users within the applicants supply chain as part of the granting of the parent authorisations. The A&D industry has responded to these requirements by increasing the level of monitoring carried out, with this including increases in expenditure on worker monitoring and adaptations to the way in which monitoring was previously carried out.

- As demonstrated in Section 4, since 2017 companies have invested in new equipment to reduce exposures to workers and to reduce environmental emissions. This has included investment in new, better performing production equipment as well as increased exhaust ventilation and other measures.

- A Binding Occupational Exposure Limit Value (OELV) has been introduced under EU Directive 2004/37/EC that will become more stringent after January 17th, 2025; this Binding OELV was recommended by the Tripartite Advisory Committee on Safety and Health based on consensus and will provide an additional level of protection for workers undertaking chromate-based electroplating.

- As indicated in the Substitution Plan, companies are progressing towards the certification and implementation of substitutes where this is already indicated as possible. Those uses that continue to take place are those where the components or the final products face the more demanding performance requirements and development of proposed candidates is ongoing.

1.7 Factors to be considered when assessing the duration of a review period

The ADCR's requirements for continued use meet the criteria set out by the ECHA Committees for Authorisation review periods longer than normal (7 years), as follows:

- **The applicants' downstream users face investment cycles that are demonstrably very long**, with this recognised in various European Commission reports. Final products in the A&D sector can have lives of over 50 years (especially military equipment), with there being examples of contracts to produce components for out-of-production final products extending as long as 35 years. MROs in particular require the ability to continue servicing older, out-of-production but in-service aircraft and equipment. The inability to continue servicing such final products will not only impact upon civil aviation but also emergency vehicles and importantly on operationally critical military equipment. Thus, although new aircraft and military equipment designs draw on new materials and may enable a shift away from the need for electroplating, there will remain a stock of in-service aircraft and equipment that will require its use as part of repairs, maintenance and overhaul activities.

- **The costs of moving to alternatives are high**, not necessarily due to the cost of the alternative substances but **due to the strict regulatory requirements that have to be met to ensure airworthiness and safety for military use.** These requirements mandate the need for testing, qualification and certification of any components using the alternatives, with this having to be carried out on all parts and components and then formally implemented through changes to design drawings and Maintenance Manuals. In some cases, this requires retesting of entire pieces of equipment for extensive periods of time, which is not only costly but may also be infeasible (due to the age of the final product, lack of testing facilities, age of available test vehicles (engines, aircraft, defence equipment, etc). On a cumulative basis, the major OEMs and DtB companies that act as the design authorities could not afford to undertake action across the range and numbers of components that still require the qualification, certification and industrialisation of alternatives. These activities themselves are costing the companies hundreds of millions of Euros across all uses of Cr(VI), and several tens of millions for electroplating alone.

- **The strict regulatory requirements that must be met generate additional, complex requalification, recertification, industrialisation activities,** to ensure the continued airworthiness of aircraft and the safety and reliability of defence equipment (including air, naval and land-based systems). These requirements mean that there is no simple or single drop-in replacement for chromium trioxide in electroplating processes, which can be considered to be "generally available" following the European Commission's definition[5]. The A&D industry has been undertaking R&D into alternatives for the past 30 years. This includes participation in research initiatives partially funded by the European Commission and national governments. Considerable technical progress has been made in developing, validating qualifying and certifying components for the use of alternatives, however, it is not technically nor economically feasible for the sector as a whole to have achieved full substitution within a four- or seven-year period. Although some companies have been able to qualify and certify alternatives for some of their components, others are still in the early phases of testing and development work due to alternatives not providing the same level of performance to chromium trioxide. They will not be able to qualify and certify a proposed or test candidate for some components within a four- or seven-year time frame. It is also of note that electroplating is used throughout the supply chain and by large numbers of smaller suppliers. As a result, sufficient time will be required to fully implement alternatives through the value chain once they have been certified.

- Even then, **it may not be feasible for military MROs to move completely away from the use of chromium trioxide in electroplating due to mandatory maintenance, repair and overhaul requirements**. MROs must wait for OEMs or MoDs to update Maintenance Manuals with an appropriate approval for each treatment step related to the corresponding aircraft components or military hardware. The corresponding timescale for carrying out such updates varies and there can be significant delays while OEMs/MoDs ensure that substitution has been successful in practice.

- In this respect, **it is important to note that the use of chromium trioxide in electroplating is required (and may be required beyond 12 years) to ensure the operational capabilities of the military and the ability to comply with international obligations as partner nations at the EU level and in a wider field, e.g. with NATO.**

- **Given the above, an Authorisation of appropriate length is critical to the continued operation of aerospace and defence manufacturing, maintenance repair and overhaul activities in the EEA and UK.** The sector needs certainty to be able to continue operating in the EEA/UK using chromium trioxide until adequate alternatives can be implemented. It is also essential to ensuring the uninterrupted continuation of activities for current in-service aircraft and defence equipment across the EEA and UK.

- As highlighted above and demonstrated in Section 5, **the socio-economic benefits from the continued use of chromium trioxide in electroplating significantly outweigh the risks of continued use**. The European A&D sector is a major exporter of final products and is facing a growing market for both its civilian and defence products which it can only serve if it retains its current strong industrial and supply chain base in the EEA and UK. It will not be able to respond to this increased market demand if the continued use of chromium trioxide in electroplating is not authorised while work continues on developing, qualifying and certifying alternatives.

- Finally, the global nature of the aerospace and defence sector must be recognised. The EEA and UK A&D sector must ensure not only that it meets regulatory requirements in the EEA and

[5] As defined with respect to the "legal and factual requirements of placing on the market" in the EC note of 27 May, 2020, available at: 5d0f551b-92b5-3157-8fdf-f2507cf071c1 (europa.eu)

UK, but also that it meets requirements in other jurisdictions to ensure that its final products can be exported and used globally.

2 Aims and Scope of the Analysis

2.1 Introduction

2.1.1 The Aerospace and Defence Chromates Reauthorisation Consortium

This combined AoA and SEA was developed by the Aerospace and Defence Chromates Reauthorisation (ADCR) Consortium on behalf of the applicants. It provides an updated assessment from that presented in the parent Applications for Authorisation (AfA) for the purposes of this Review Report (RR). For the purposes of this document, the term 'aerospace and defence' (A&D) comprises the civil aviation, defence/security and space industries.

It covers the use of chromium trioxide (CT) for electroplating by the ADCR consortium members and companies in their supply chain, taking into account the needs of their supply chains. The scope is the same as the original CTAC parent application (see Section 2.2), with the use defined as:

> *"Electroplating using chromium trioxide in aerospace and defence industry and its supply chains".*

Electroplating, also known as hard chrome plating, is used to increase wear resistance and hardness. It is applied as a main treatment, mainly on plain metal substrates. The use of chromium trioxide in electroplating is limited to those situations where it plays a critical (and currently irreplaceable) role in meeting product performance, reliability, and safety standards, particularly those relating to airworthiness set by European Aviation Safety Agency (EASA). This is also true with respect to the use in defence and in aerospace derivative products including space, which have to comply with numerous comparable requirements including those of the European Space Agency (ESA) and of national MoD.

This is an upstream application submitted by manufacturers, importers and/or formulators of chromium trioxide for electroplating. It is an upstream application due to the complexity of the A&D supply-chain, which contains a large number of small and medium-sized enterprises (SME). The ADCR was specifically formed to respond to this complexity and to benefit the entire supply chain, thereby minimizing the risk of supply chain disruption. The aim is also to provide the industry's major OEMs and DtB manufacturers with flexibility and to enable them to change sources of supply for the manufacture of components; it also helps ensure that choice of supply, competition and speed of change is maintained. The importance of this type of risk minimization has become only too apparent due to the types of supply chain disruption that has arisen due to COVID-19.

As a result, the analysis presented here is based on an extensive programme of work funded and carried out by the main OEMs and DtBs, and key suppliers where this includes small, medium and other large actors within the sector. It is based on sector-specific data and detailed information obtained from the ADCR members (which includes OEMs, DtBs, BtPs, MROs and MoDs) and collected from their A&D suppliers throughout the supply chain. In total, data were collected from companies covering over 260 A&D sites in the EEA and UK, with data for 68 of those sites used in developing this combined AoA/SEA.

It is also important to confirm that the parent AfA (0032-02) in the scope of this review report include the use of chromium trioxide in electroplating as part of the production of aeroderivative gas turbines and engines, referred to simply as "aeroderivatives". These are products that use components and designs adapted from the designs and relying on the supply chains that produce aircraft gas turbines. Aeroderivative products make up a small percentage (1 – 2%) of the total A&D

hardware volume in the European Union (EU) (UK figures are unavailable but are likely to be higher) and are used to generate electricity or propulsion in civil and defence marine, oil and gas, and industrial applications. As the components used in aeroderivatives are designed to the same thresholds as aerospace and produced in the same manufacturing lines, the same arguments for the use of the components treated with chromium trioxide in the aerospace industry apply to aeroderivatives. High performance requirements are mandatory for aeroderivatives, as well as for aerospace components due to operation in harsh and corrosive environments (e.g. at sea). Aeroderivatives are distinct from pure industrial engines and similar support equipment which are not covered by this review report.

In addition, in order to ensure consistency and continuity of global supply chains under both EU REACH and UK REACH, this document covers the requirements of A&D supply chains in both the EEA and the UK. Where important, information is separated out for the EEA and UK, so that authorities in both jurisdictions have a clear view of impacts.

2.1.2 Aims of the combined AoA and SEA document

The downstream users supporting the ADCR consortium have no qualified (from a technical perspective) and economically feasible alternatives which can be fully implemented across all products, components and MRO processes before the expiry of the original authorisations, and must continue to use CT in electroplating activities in the EEA and UK, including in formulations, as they are fundamental and integral to providing wear resistance and preventing corrosion of aerospace components.

Although the A&D sector has been successful in implementing alternatives in certain applications with less demanding requirements, the aim of this Review Report (RR) is therefore to allow the continued use of CT in electroplating beyond the end of the existing review period which expires in September 2024, for the processes where alternative implementation has not yet been successful. It demonstrates the following:

- The technical and economic feasibility, availability, and airworthiness (i.e. safety) challenges in identifying an acceptable alternative to the use of chromium trioxide, which does not compromise the functionality and reliability of the components treated by electroplating and which could be validated by OEMs and gain certification/approval by the relevant aviation and military authorities across the globe;

- The R&D that has been carried out by the OEMs, DtBs and their suppliers towards the identification of feasible and suitable alternatives for CT in electroplating. These research efforts include EU funded projects and initiatives carried out at a more global level, given the need for global solutions to be implemented within the major OEMs' supply chains;

- The efforts currently in place to progress proposed candidates through Technology Readiness Levels (TRLs), Manufacturing Readiness Levels (MRLs) and final validation/certification of suppliers to enable final implementation. This includes treatment of components for civilian and military aircraft and defence equipment that continue to be produced, as well as for maintenance, repair and overhaul of those products and out-of-production civilian and military aircraft and other defence systems;

- The socio-economic impacts that would arise for ADCR downstream users and their suppliers, their upstream and downstream supply chains and, crucially, for the EEA and UK more generally, if the applicants were not granted re-authorisations for the continued use of CT over an appropriately long review period; and

- The overall balance of the benefits of the continued use of CT to the risks to human health from the carcinogenic and reprotoxic effects that may result from exposures to CT.

It should be noted that this combined AoA/SEA is one of a set that has been prepared by the ADCR Consortium to cover the range of different uses of the chromates that continue to be required by the EEA (and UK) A&D industries.

2.2 The parent Application for Authorisation

This combined AoA/SEA covers only the use of CT in electroplating:

- Chromium trioxide (includes "Acids generated from chromium trioxide and their oligomers", when used in aqueous solutions) EC 215-607-8 CAS 1333-82-0

Note, there are currently authorisations for use of sodium dichromate and potassium dichromate in electroplating, however, ADCR members advise that the use of these chromates is no longer needed.

Chromium trioxide (CT) was included in Annex XIV of REACH (Entry No. 16) due to its carcinogenic (Cat. 1A) and mutagenic properties (Cat. 1B). As CT is mainly used in aqueous solution in electroplating, this combined AoA/SEA also covers the acids generated from CT and their oligomers (Entry No. 17). In the remainder of this document, references to CT always include the acids generated from CT and their oligomers.

Authorisations were granted for the continued use of chromium trioxide in electroplating to a range of applicants, as summarised in **Table 2-1**. These are the parent applications to this Review Report.

Table 2-1: Overview of Initial Parent Applications for Authorisation

Application ID/ authorisation number	Substance	CAS #	EC #	Applicants	Parent Authorisation – Authorised Use
0032-02 REACH/20/18/7 REACH/20/18/9 REACH/20/18/11	Chromium trioxide	1333-82-0	215-607-8	ChemServices as OR for Brother; Boeing Distribution Ltd; Cromital (CTAC consortium)	Functional chrome plating

2.3 Scope of the analysis

2.3.1 Brief overview of uses

2.3.1.1 Process description

Electroplating (or functional chrome plating) involves formation of a metal coating on a component by an electrochemical method (electrolysis). As carried out by ADCR members, it involves the use of chromium trioxide in order to create a wear resistant, hard chrome coating. This coating also provides corrosion resistance to the electroplated component.

During the process, the component to be treated, which serves as a cathode, is immersed into an electrolyte containing CT, as well as additives and an anode (e.g., inert material or block of metal). While an external electric current is applied, the Cr(VI) cations of the electrolyte are reduced and deposited forming a suitable adhered metallic chrome coating that protects the substrate (increased hardness as well as wear, abrasion, and corrosion resistance).

The reaction that takes place during electroplating reduces the Cr(VI) into Cr(0), thus leaving no Cr(VI) on the surface layer of the electroplated component. The understood overall reaction is as follows:

Cathode: $Cr^{6+} + 3\ e^- \rightarrow Cr^{3+}$ and $Cr^{3+} + 3\ e^- \rightarrow Cr^0$

Anode: $Cr^{3+} \rightarrow Cr^{6+} + 3\ e^-$

Electroplating is in most cases carried out by immersion of components into treatment baths. Typically, the treatment baths are positioned in a large hall where baths for other immersion processes are also present; some of these baths might also involve the use of Cr(VI) although they may be unrelated to the present use. The immersion tanks can be placed individually or within a line of several immersion tanks. Usually, at least one rinsing tank with water is positioned after an immersion tank, for rinsing off the electroplating solution from the component(s). The figure below shows a treatment bath for electroplating with an anode.

Figure 2-1: Electroplating treatment bath

A variety of substrates are electroplated. Often the components are made of steel or stainless steel. However, also aluminium, copper, cast iron, and different alloys (e.g., brass, Al-Ni-Bronze) can be used as a substrate.

Whilst this process is used by most ADCR members in the way described above, the same process can also be applied using a non-reflective black chrome (for functional rather than decorative purposes). This is particularly relevant for defence products such as military diving equipment.

2.3.1.2 Relationship to other uses

As shown in **Figure 2-2** below, electroplating with CT is usually combined with pre-treatments (e.g., degreasing, etching) and post-treatments. The pre-treatments (e.g., pickling/etching, degreasing) can involve chromates or not, except for alkaline cleaning which is solely performed Cr(VI)-free. In some cases, components may be etched in the electroplating baths (reverse etching, without removing the components) rather than in a separate pre-treatment bath. After electroplating, components may undergo a post-treatment, which can contain (Cr(VI), e.g., impregnation with resins or primers) or is Cr(VI) free (e.g., heating or application of an additional coating/impregnation) depending on the mandated requirements for the specific component. In cases of defective finishing or as part of rework processes, chemical or electrochemical removal of the Cr(0) layer of electroplated components is performed under acidic or alkaline conditions containing no Cr(VI). Additionally, mechanical removal of the electroplated coating may also be performed. For the combination with deoxidising/ etching/desmutting with CT or SD, all details on these pre-treatment processes are described in the CSR on "Pre-treatments".

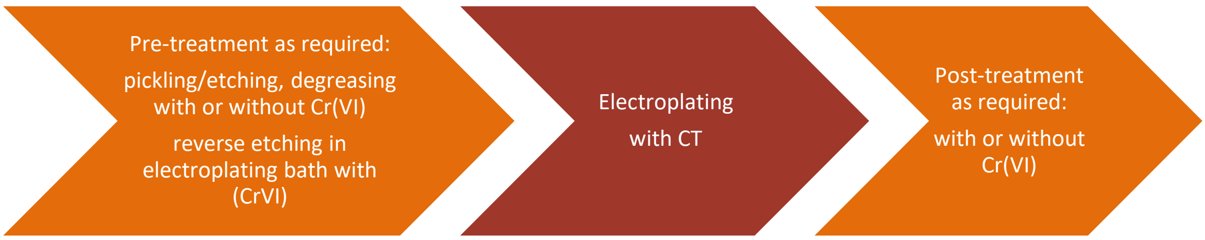

Figure 2-2: Schematic presentation of treatment steps

Please see the other ADCR re-authorisations dossiers for further details of these other processes, the availability of alternatives and the socio-economic impacts of a refused re-authorisation.

2.3.2 Temporal scope

Because of the lack of qualified and viable alternatives for the use of chromium trioxide in electroplating for aerospace components, it is anticipated that it will take a minimum of a further 12 years to develop, qualify, certify and industrialise alternatives across all components. Over this 12-year period, the temporal boundaries adopted in this assessment take into account:

- When human health, economic and social impacts would be triggered;
- When such impacts would be realised; and
- The period over which the continued use of chromium trioxide would be required by the A&D industry as a minimum.

The impact assessment periods used in this analysis and the key years are presented in **Table 2-2**.

Table 2-2: Temporal boundaries in the analysis			
Present value year		2021	
Start of discounting year		2024	
Impact baseline year		2024	
Scenario	**Impact type**	**Impact temporal boundary**	**Notes**
"Applied for Use"	Adverse impacts on human health	12 years, following a 20-year time lag	Based on the length of requested review period
"Non-use"	Loss of profit along the supply chain	12 years	Based on the length of requested review period
	Impacts on growth and GDP	12 years	Based on the length of requested review period
	Disruption to EEA society due to impacts on civil, emergency, and military aviation, as well as defence equipment	12 years	Based on the length of requested review period
	Loss of employment	1 to over 3 years	Average period of unemployment in the EEA (Dubourg, 2016)

2.3.3 The supply chain and its geographic scope

2.3.3.1 The ADCR Consortium

The ADCR is composed of 67 companies located in the EEA and the UK that act as suppliers to the A&D industry (17 importers, formulators and distributors) are active downstream users (OEMs, DtBs or BtPs), or are MRO providers (civilian or military) within the industry sector. Membership also includes Ministries of Defence (MoDs) due to concerns over the loss of the availability of the chromates for on-going maintenance and repair of military equipment.

Of the downstream user members, 24 comprise the leading OEMs, Design-to-Build (DtB)and MROs operating in the EEA and UK. These 24 large companies operate across multiple sites in the EEA, as well as in the UK and more globally. It is these leading OEMs and DtB companies that act as design owners and establish the detailed performance criteria that must be met by individual components and final products to ensure that airworthiness and military requirements are met. A further 21 small and medium sized companies joined the ADCR to ensure the success of the consortium in re-authorising the continued use of the chromates and to share their information and knowledge. These companies are involved in BtP, DtB and MRO activities, sometimes acting as a combination of these.

Most of the large ADCR members (17 of the 24) support the use of chromium trioxide for electroplating; as noted earlier, this may be either for their own use or for use in their supply chains. The large members may be supporting the use of electroplating by their suppliers (who must use the chromates to meet their OEM's and DtB's contractual requirements), rather than undertaking the use themselves. As a result, the scope of this analysis covers an assessment of the impacts on suppliers carrying out electroplating, as well as on their ADCR customers.

2.3.3.2 Suppliers of chromate substances and mixtures

Three generic electroplating products have been identified as listed in **Table 2-3** below.

Table 2-3: Products used in electroplating	
Product A	Solid chromium trioxide (flakes), pure substance (100%); 52% Cr(VI)
Product B	Solid mixture containing chromium trioxide (10-40%); <21% Cr(VI)
Product C	Aqueous solution of chromium trioxide as purchased (up to 50% (w/w)); max. 26% (w/w) Cr(VI)

Chromium trioxide is not manufactured within the EEA or UK, rather it is imported either in substance form, and may then be formulated (Product C) for use in electroplating. Products may be sourced through distributors that operate both nationally and across the EU.

2.3.3.3 Downstream users of chromium trioxide for electroplating

Electroplating within the A&D sector is performed exclusively in industrial settings. The downstream users of chromium trioxide can be broadly categorised as follows:

- Original equipment manufacturer (OEM) – generally large companies which design, manufacture, assemble and sell engines, aircraft, space and defence equipment to the final customer;
- Design-to-Build[6] (DtB) – companies which design and build components and sub-systems;
- Build-to-Print (BtP) – companies that undertake specific processes, dictated by their customers, involving chromium trioxide on components; and
- Maintenance, Repairs and Overhaul (MRO) – companies that service aircraft, space and defence equipment.

Commercial aircraft, helicopter, spacecraft, satellite and defence manufacturers are involved in the supply chain, and in the use of the chromates for electroplating of critical components essential to the manufacturing of their final products.

It is important to note that companies may fit into more than one of the above categories, acting as an OEM, DtB, and MRO[7], where they service the components they designed and manufactured, and which are already in use. Similarly, a company may fall into different categories depending on the customer and the component/final product.

The complexity of the supply chain relationships is illustrated in **Figure 2-3** below, with this highlighting the global nature of these relationships and the interlinkages that exist between suppliers in different geographic regions.

[6] Also referred to as "design and make" or "design responsible" suppliers.

[7] Also common are companies categorising themselves as a BtP and MRO.

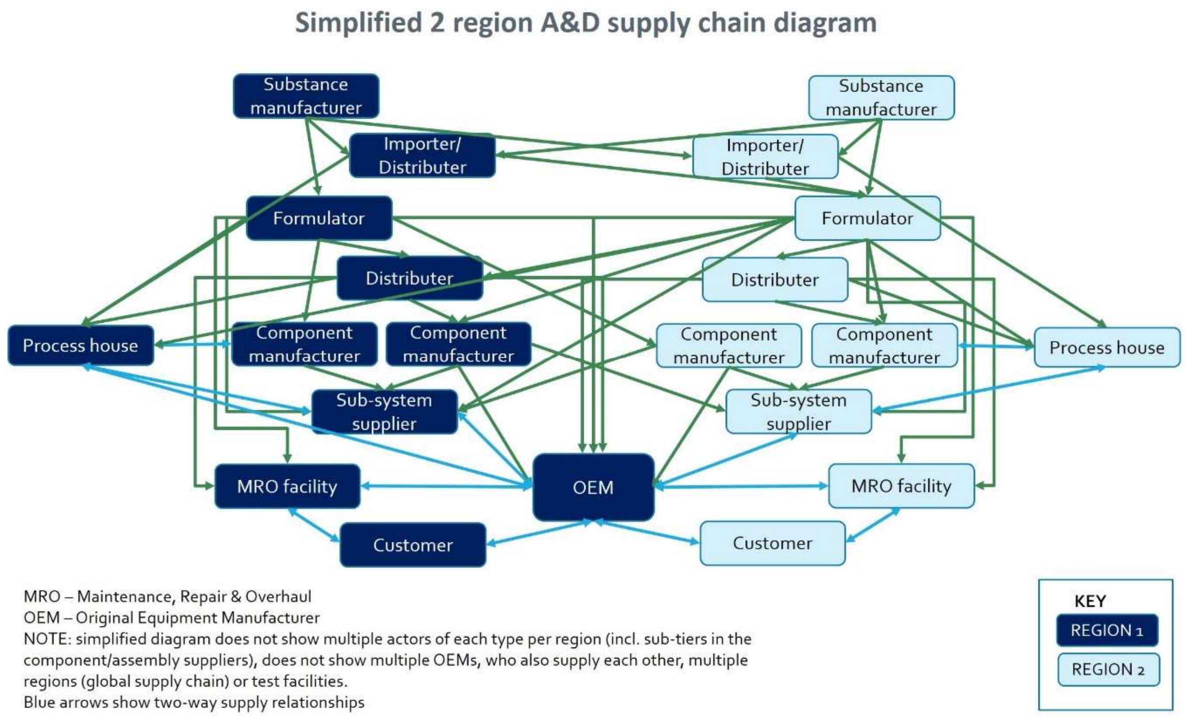

Figure 2-3: Complexity of supply chain roles and relationships within the A&D sector

The assessment provided in this combined AoA/SEA is based on the following distribution of companies by role, where this includes ADCR members and their suppliers involved with electroplating. It is important to note that these companies operate across multiple sites within the EEA and/or UK, with the total number of sites covered by the data provided also reported below. Note that the number of OEMs providing data for this SEA is smaller than the number of ADCR OEM members supporting this use, as they rely on operators within their supply chain to undertake such activities.

It is important to note the numbers of BtP and MRO companies and associated sites that provided data on electroplating activities. This has implications for the level of effort required by design owners (OEMs and DtB companies) in implementing an alternative throughout their value chains.

Table 2-4: Numbers of companies providing SEA information on electroplating

Role	Number of companies	Number of sites
OEMs	7	26
Design-to-Build	12	19
Build-to-Print	13	16
MRO mainly (civilian and/or military)	5	7
Total	37	68

2.3.3.4 OEMs, DtB and BtP Manufacturers

While the OEMs do undertake electroplating, it is clear that electroplating is also carried out by a range of companies within the supply chain. In the case of EEA/UK-based OEMs, these suppliers are often located in the same country (if not the same region) as their main OEM customer.

The OEMs will often act as the design owner and define the performance requirements of the components required for an aerospace, defence or space product, as well as the materials and processes to be used in manufacturing and maintenance. They may undertake electroplating as do their suppliers. As design owners, OEMs are responsible for the integration and validation of the final product and certification approval. The OEMs may themselves treat components in a similar manner to their suppliers. They operate at the global level, and therefore may have facilities both in the EEA, the UK and located in other regions. They may also be global exporters of final A&D products.

DtB manufacturers develop in-house designs to meet the performance requirements of their customers, and therefore will also act as design owners. These suppliers may have more control over the substances that they use in manufacturing their components but must still ensure that they achieve the strict performance requirements set by OEMs. They may carry out research into alternatives and act as test facilities for their customers.

BtP manufacturers produce components to the technical drawings provided by their customers, which often mandate directly (on the drawing) or indirectly the specific formulations to be used to meet the performance requirements set by their customers. The components are then used by DtBs or OEMs in the final production of aircraft and defence and space equipment. These suppliers have no choice in the substances that they are required to use within their processes. They, therefore, carry out no research into alternatives (although they may act as test facilities for their customers).

A BtP supplier may be requested to sign a manual or code of conduct by the OEM, to ensure expectations for work and awareness of requirements is achieved. Once the BtP supplier is qualified, periodic audits are performed to ensure continued compliance with contractual requirements

2.3.3.5 Maintenance, Repair and Overhaul

Products for the A&D industry are designed, manufactured and maintained for service lives of several decades. In terms of civil aircraft and defence systems, service life typically comprises 30-40 years. MRO shops carry out the maintenance, repair, and overhaul activities involved in ensuring that aircraft, defence and space equipment and hardware continue to meet airworthiness and safety requirements. This includes electroplating as a portion of such activities.

A representative life cycle of a typical aerospace product – a commercial aircraft - is illustrated in **Figure 2-4**. This highlights that: the development of a new aerospace system can take up to 15 years; the production of one type of aerospace system may span more than 50 years; and the lifespan of any individual aircraft is typically 20-30 years. **Figure 2-5** provides an overview of the life cycle of weapon systems, which are usually used much longer than the originally projected lifetime. Such life cycles can be significantly longer than 50 years. For such systems, it is extremely costly to identify and replace legacy applications of chromium trioxide without impacting performance, where performance has been assured for many decades.

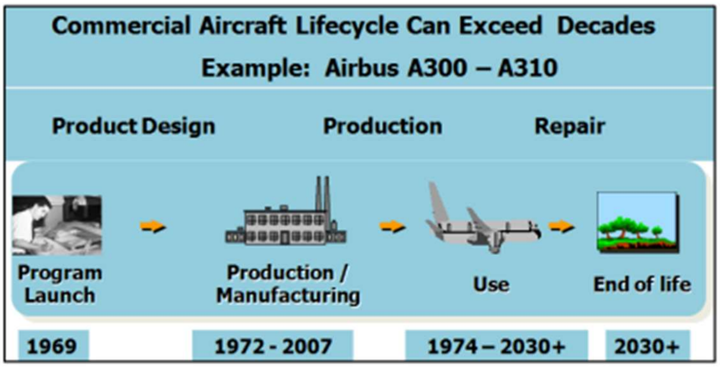

Figure 2-4: Commercial Aircraft Service Life, from ECHA & EASA (2014)[8]

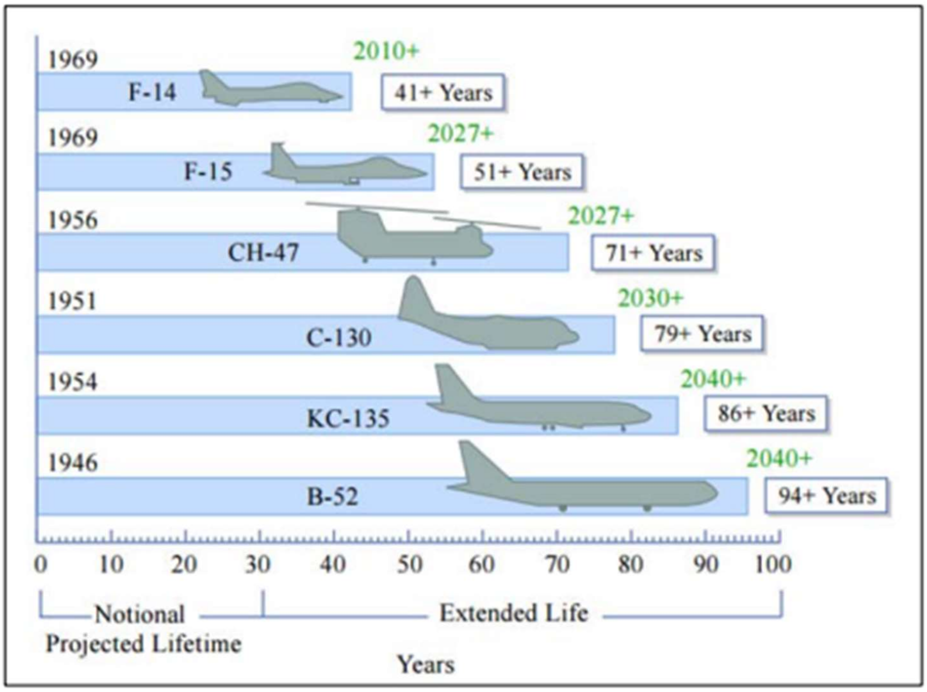

Figure 2-5: Life cycles of defence aircraft, from A Haggerty (2004)[9]

Even if new designs/components – coming onto the market in the short to medium term – might succeed in dispensing with the use of CT based electroplating, products already placed on the market still need to be maintained and repaired using CT based electroplating until suitable alternatives are validated for use in MRO for those existing products. Maintenance manuals for such existing products (which the user is legally obliged to comply with) detail, amongst other information, the processes and materials initially qualified (sometimes decades ago) and required to be used, which form a substantial portion of the type certification.

[8] https://www.easa.europa.eu/en/document-library/general-publications/echa-easa-elaboration-key-aspects-authorisation-process

[9] https://studylib.net/doc/13484803/lifecycle-considerations-aircraft-systems-engineeering-al...

As a result, MROs face on-going requirements to undertake electroplating, in strict adherence to the requirements of qualified repair and maintenance schemes to ensure continued safe operation of the final A&D products.

2.3.3.6 Estimated number of downstream user sites

Based on the information provided by 15 OEM and DtB ADCR members, it appears that each of these has, on average, between seven to ten approved suppliers and/or their own sites involved in electroplating (one member listed a potential 27 sites). However, four of these OEM companies are UK focused and have therefore been excluded from EEA estimates. The estimated number of sites in the EEA is therefore 125 within the ADCR supply chain and taking into account overlap in the suppliers to different ADCR members.

For the UK, based on the information provided by the OEMs and DtB companies, as well as considering relevant members of the Institute of Materials Finishing and Surface Engineering Association, it would appear that there are approximately 25 sites involved in electroplating.

Under Article 66 of REACH, downstream users covered by an authorisation up their supply chain must notify ECHA of their use. As of 31 December 2021, ECHA had received 526 notifications relating to the various REACH Authorisations listed above as well as 31 notifications relating to REACH/20/17/1 covering between them 619 sites across the EU-27 (and Norway). The distribution of notifications by substance and authorisation is summarised below.

There are more sites than notifications, reflecting the fact that some notifications cover more than one site[10]. As would be expected the number of sites is far in excess of the 100 sites estimated above. This is because the authorisations relate to functional chrome plating which is used in many industry sectors, including automotive and general engineering as well as A&D.

There is no comparable publicly available data for the UK, so estimates for the UK rely on information from the ADCR members and its SEA Expert Group. HSE did not provide data on the number of notifications made under UK REACH in time for incorporation into this assessment.

With these points in mind, the estimated 125 EEA sites to be covered by this review report and by the ADCR applicants is believed to be consistent with the ECHA data on Article 66 downstream user notifications. This number of sites also reflects the fact that not all of the original CTAC applicants are supporting the ADCR, with this expected to lead to some changes in the number of customers being supplied the chromium trioxide by the ADCR applicants. In addition, the figure of 125 sites takes into account the fact that some of the A&D sector will be covered by the non-ADCR applicants.

[10] Article 66 reporting is by legal entity, which can have multiple sites using CT for electroplating. Closer inspection of the (publicly available) data from ECHA suggests that some sites are associated with confidential military activities. These may or may not be relevant to the ADCR given that members include Ministries of Defence (MoDs) and information has been provided by non-member military organisations.

Table 2-5: Electroplating downstream uses notified to ECHA				
Substance	**Authorisation**	**Authorised Use**	**Notifications**	**Sites**
Chromium trioxide	20/18/7-13	Functional chrome plating	526	619
	20/17/1	Functional chrome plating	31	
Source: Number of downstream uses covered by granted authorisations as notified to ECHA by 31 December 2021, data available from https://echa.europa.eu/du-66-notifications				

2.3.3.7 Geographic distribution

The distribution of the 619 sites notified to ECHA is summarised in the table below. This is considered to also be reflective of the distribution of A&D sites undertaking electroplating.

Table 2-6: Number of authorised sites using chromium trioxide for Functional Chrome Plating notified to ECHA as of 31 December 2021		
Country	Notified Sites	% Total
Germany	178	29%
Italy	143	23%
France	63	10%
Spain	50	8%
Poland	45	7%
Czech Republic	25	4%
Sweden	15	2%
Austria	13	2%
Greece	12	2%
Netherlands, Belgium, Hungary	10 each	2% each
Romania, Bulgaria, Norway, Denmark, Slovakia, Slovenia	4-9 each	c 1% each
Finland, Ireland, Portugal, Malta, Croatia	1-3 each	< 0.5% each
EU-27 plus Norway	**619**	
Number of sites relates to specific authorisations listed in previous table.		

2.3.3.8 Customers

The final actors within this supply chain are customers of A&D final products treated via electroplating.

With respect to civil aviation, the global air transport sector employs over 10 million people to deliver in a normal year some 120,000 flights and 12 million passengers a day. In 2017, airlines worldwide carried around 4.1 billion passengers. They transported 56 million tonnes of freight on 37 million commercial flights. Every day, airplanes transport over 10 million passengers and around US$ 18 billion (€16 billion, £14 billion) worth of goods. The wider supply chain, subsequent impacts and jobs in tourism made possible by air transport show that at least 65.5 million jobs and 3.6% of global economic activity are supported by the industry.[11] More specifically to Europe, in 2019 over 1 billion passengers travelled by air in the European Union, with net profits of over US$ 6.5 billion (€5.8 billion, £5.1 billion).[12] These benefits cannot be realised without the ability to undertake regular maintenance

[11] https://www.icao.int/annual-report-2020/Pages/the-world-of-air-transport-in-2020.aspx

[12] https://www.statista.com/statistics/658695/commercial-airlines-net-profit-europe/

works and to repair and maintain aircraft as needed with replacement components manufactured in line with airworthiness approvals.

In 2020, total government expenditure on defence across the EU equated to 1.3% of GDP, with Norway spending around 2% of GDP[13]. Roughly 38% of this expenditure related to military aviation. The dynamics of the military aircraft development and market are significantly different than for commercial aircraft. Military aircraft are extremely expensive and specialised projects. As a result, to have an effective military force, Ministries of Defence require equipment that is well-maintained and mission ready. Although the in-service military fleet is expected to grow rapidly in the future, older aircraft and other equipment will continue to require more frequent scheduled maintenance to replace components that are reaching the end of their "component life", which would not have needed replacing on younger aircraft. Upgrades will also be required to extend the service life of aging aircraft given the costs of new military aircraft. Maintenance of aircraft and products is already reported to face difficulties due to material obsolescence issues over the extremely long service lives of such hardware. A major issue is obtaining readily available components for the vast number of aircraft flying beyond their originally expected lifecycles.

2.4 Consultation

2.4.1 Overview

Three types of consultation were undertaken for the purposes of this combined AoA/SEA:

- Consultation with the Applicants (importers and formulators) to gather Article 66 downstream user notifications data, and information on volumes placed on the market and numbers of customers; this has included consultation with the formulators to gather information on their efforts to develop alternatives on their own, in collaboration with the downstream users, and as part of research projects funded by national governments, the EC and more internationally.

- Consultation with ADCR members to gather information on their uses, supply chains, R&D into alternatives, qualification processes and responses under the non-use scenario;

- Consultation with component and special process suppliers within the aerospace and defence supply chain to gather socio-economic information, ability to move to alternatives and likely responses under the non-use scenario.

Further details of each are provided below.

2.4.2 Consultation with Applicants

Information was gathered from the applicants on their supply chains and on quantities sold per annum. The applicants may act as an importer, a downstream user (e.g. formulator, distributor involved in repackaging) and/or as a distributor for other applicants/formulators of CT for use in electroplating

[13] *Source:* Eurostat (gov_10a_exp)

Only a minimal amount of economic data was collected from the applicants, as losses in profits to this group of companies is not what drives the requested re-authorisations by this Review Report. Information on alternatives and substitution was, however, collected.

2.4.3 Consultation with Downstream users

2.4.3.1 ADCR Consortium Members

Consultation with ADCR members was carried out over a period from 2019 to 2022 to collect a range of data relevant to both the AoA and the SEA. This consultation was carried out with all downstream user members of the ADCR (i.e. members located in both the EEA and UK), and regardless of their role within the supply chain. Consultation took place over different phases:

1) Phase 1 involved collection of information on surface treatment activities that each member undertook. This included:
    a. Supply chains
    b. Substances used in each activity and associated volumes
    c. Key functions provided by the substance
    d. Locations for each activity
    e. Likelihood of substitution before 2024

2) Phase 2 involved collection of data on R&D activities undertaken by each company. This included confidential and non-confidential information on:
    a. Successes and failures
    b. Alternatives tested and for what uses
    c. Reasons for failures, where this was the outcome
    d. Alternatives still subject to R&D and their progression in terms of technical readiness, and if relevant manufacturing readiness

3) Phase 3 then took the form of detailed one-on-one discussions between ADCR members and the AoA technical service team. The focus of these discussions was to ensure:
    a. Additional critical details were collected concerning core aspects of the AoA/SP portions of the Authorisation dossiers (e.g. clarify R&D and substitution timelines and address outstanding questions regarding alternatives and their comparative performance).

4) Phase 4 collected information for the SEA component of this document, with this including:
    a. Base data on the economic characteristics of different companies
    b. Additional information on volumes used of chromium trioxide and for what processes, and trends in this usage over the past seven years and as anticipated into the future
    c. The importance of chromate-using processes to the turnover of individual companies
    d. Past investments in R&D into alternatives
    e. Past investments into capital equipment related to on-going use of chromium trioxide as well as to their substitution; this included investment in new facilities outside the EEA
    f. The most likely non-use scenario for each use and the required review period including a justification for the required period

g. Numbers of employees directly involved in use of chromium trioxide as well as the total number of employees at sites that would also be directly impacted under the non-use scenario
h. Economic and social impacts under the non-use scenario.

It is important to note that as work progressed over these different phases of consultation, members identified reduced needs with respect to the on-going use chromium trioxide for electroplating. In particular, the use of sodium dichromate and potassium dichromate is no longer required by the original set of members identifying this as needed in 2019.

2.4.3.2 Build-to-Print and Design-to-Build suppliers to ADCR members

SEA questionnaires were also developed for completion by suppliers to the ADCR members. This included separate questionnaires for BtP and DtB suppliers given their different roles within the supply chain and the potentially greater flexibility for DtB suppliers to move to alternatives as part of their own design activities.

These questionnaires were distributed to key suppliers by the larger ADCR members and were also made available to any company within the ADCR supply chain requesting they provide information and participate in the re-authorisation work. The scope of these questionnaires was similar to that described above for the ADCR members.

As a final count, data for 68 sites operated by the OEMs and their BtP and DtB suppliers provided responses to these questionnaires. The information provided by these companies forms the basis for the SEA component of this document.

2.4.3.3 MROs

For consistency purposes, MROs were asked to also complete the BtP questionnaires. Again, these were supplied directly to MROs or were distributed by ADCR members to their key suppliers. MoDs were also asked to participate in the work and a number of military MROs provided data on their activities to ensure that these would also be covered by a renewed Authorisation. Their data is included in the SEA as appropriate to their activities.

3 Analysis of Alternatives

3.1 SVHC use applied for

3.1.1 Overview of key functions

The definition of electroplating, as agreed by ADCR members, is:

> "*Electroplating is the formation of a metal coating on the part [component] by an electrochemical method in an electrolyte containing metal ions and the part is the cathode, an appropriate anode is used, and an electrical current is applied.*"

Electroplating using chromium trioxide involves immersion of the component in a series of treatment baths containing chemical solutions or rinses under specific operating conditions.

It should be noted that in the function of Cr(VI)-based electroplating, the process can also be referred to as both hard chrome plating and functional chrome plating.

The substrates that have been reported as being relevant for electroplating are:

- Aluminium and aluminium alloys
- Bronze
- Copper and copper alloys
- Cast iron
- Low alloy steels
- Nickel and nickel alloys
- Stainless steel
- Steel/hardened steel
- Various metals and metal alloys

The key functions of chromium trioxide in electroplating were identified in the Implementing Decision of the parent Authorisation and are as follows:

- Wear resistance;
- Corrosion resistance;
- Hardness;
- Coefficient of friction;
- Layer thickness; and
- Effect on surface morphology.

As described in Section 2.3.1.1, the following reactions are thought to take place during electroplating:

Cathode: $Cr^{6+} + 3e^- \rightarrow Cr^{3+}$ and $Cr^{3+} + 3e^- \rightarrow Cr^0$
Anode: $Cr^{3+} \rightarrow Cr^{6+} + 3e^-$

The substrate is submerged in an electrolytic plating solution containing dissolved metal salts and additives. Electroplating enhances the hardness, wear and abrasion resistance of the substrate, and can improve corrosion resistance. Chromium is the third hardest element based on the Mohs hardness scale, behind only carbon (diamond) and boron, so relates to very hard wear resistant coatings (Reade Advanced Materials, 2015).

Electroplating with chromium trioxide is usually combined with pre-treatments (e.g., degreasing, etching) and post-treatments. The pre-treatments (e.g., pickling/etching, degreasing) can involve chromium trioxide or not, except for alkaline cleaning which is solely performed Cr(VI)-free. In some cases, components may be etched in the electroplating baths (reverse etching, without removing the components) rather than in a separate pre-treatment bath. Following electroplating, components may undergo a post-treatment step, which can contain Cr(VI), (e.g., impregnation with resins or coating with primers) or be Cr(VI)-free (e.g., heating or application of an additional coating/impregnation). For components with very specific requirements, sometimes passivation using sodium dichromate is performed either prior to or after electroplating. In cases of defective finishing or as part of rework processes, chemical or electrochemical removal of the metallic chrome layer of the electroplated components is performed under acidic or alkaline conditions containing no Cr(VI). Additionally, mechanical removal of the electroplated coating may also be performed.

Pickling involves the substrate being treated with a chromium trioxide-based pickling solution which removes surface oxides and a small amount of the substrate surface (0.4-0.6µm). This reduces the effects of any surface oxidation of the substrate which has taken place in manufacture, storage, or transport (Jungeun Lee, et al., 2020).

The etching process involves the treatment of the substrate using the same action as pickling, however to a greater extent. A substrate undergoing etching is immersed in a bath of aqueous acidified solution which removes defects, oxides, and surface layers of the substrate (typically 2-4µm every 5 minutes). This process can also be referred to as surface activation and may be repeated in cases such as following intermediate plating of copper (Kim *et al.*, 2013).

The micro-structure and aspect of the electroplated deposit can be heavily influenced by the chemical constituents of the electrolyte, temperature, current density, level of agitation, and other variables within the electrodeposition process (Luo *et al.*, 2006). The microstructure of the deposit can be altered to be crack-free, micro-cracked or macro-cracked. As the ductility of the crack-free coating is poor, this often results in macro-cracking of the coating in use, which reduces corrosion resistance and can promote spalling. Micro-cracked hard chromium is an incredibly useful structure considering the features it provides.

The micro-structure of the chrome coating is influenced by the way the hydrogen evolution is controlled, and the evolution of the chrome film being deposited on the cathode (Jones, 1989). The microstructure of the chrome coating ranges from tight coatings with inner tension to tension-free coatings with up to 2,000 micro-cracks per cm. The chrome is deposited in a hexagonal crystal, reorganising itself into a tighter body-centred cubic structure and setting free the built-up hydrogen.

Oxygen also plays a part in the functional performance of the coating, but not the actual plating process (Brenner, Burkhead and Jennings, 1948). Given the tendency of chromium to form chromium oxide on the surface, there is some speculation on the role of chromium oxide in the functional performance of the coating. Depending on the coating and the process, it may play a role in the functional response. It is possible that micro-cracks on the surface of the material can act as lubricant reservoirs to aid the functional performance of the chromium plating solution (Erikson, 2014).

3.1.1.1 Usage

Parts and assemblies that may be treated with the Annex XIV substance

As detailed above, electroplating, like all surface treatments, aims to modify the surface of the substrate to improve the substrate properties and adapt it to its specific use conditions. There are many corrosion and wear prone areas on A&D products which require the application of surface treatments. Examples of these are included in **Table 3-1** below.

Table 3-1: Examples of corrosion and wear prone areas of A&D products (non-exhaustive)

Structural/flight	Propeller/rotor	Engine/power plant	Additional Space- and Defence-specific
Aileron and flap track area	Blade tulip and hub	Auxiliary Power Units (APUs)	Air-transportable structures
Centre wing box	Gearbox	Carburettor	Fins
Cockpit frames	High bypass fan components	Data recorders	Gun barrels and ancillaries
Differential	Main and tail rotor head assemblies	Engine Booster and Compressors including Fan Containment	Interstage Skirts
Emergency valve landing gear	Propeller speed controller	Engine control unit	Launchers (rocket, satellite, etc.)
Environmental control systems	Propellers	Engine External components	Missile and gun blast control equipment
External fuel tanks	Transmission housing	Fuel pump	Missile launchers
Flight control systems		Gearbox	Pyrotechnic Equipment
Fuselage		Hydraulic intensifier	Radomes
Hydraulic damper		Ram air turbine	Rocket motors
Hydraulic intensifier		Starter	Safe and arm devices
Landing equipment		Vane pump	Sonar
Nacelles			
Pylons			
Rudder and elevator shroud areas			
Transall (lightning tape)			
Undercarriage (main, nose)			
Valve braking circuit			
Window frames			
Wing fold areas			
Source: (GCCA, 2017)			

It is important to note that even with the highly developed Cr(VI)-containing treatments available, corrosion and wear of these components still occurs, however decades of experience relating to the appearance and impacts of corrosion on Cr(VI) systems allows the A&D industry to define inspection, maintenance and repair intervals.

Cr(VI)-free alternatives cannot be introduced where they are known to result in a decreased performance in key functions, since some or all of the following consequences may occur:

- Substantial increase in inspections, some of which are very difficult or hazardous to perform;

- Increased overhaul frequency or replacement of life-limited components;
- Possible early retirement of A&D products due to compromised integrity of non-replaceable structural parts;
- Whole fleets may be grounded until a repair/replacement plan is in place for the whole aircraft fleet - This could impact many or all aircraft fleets. Defence systems would be similarly impacted, affecting the continuity of national security;

In addition to the above, there may be limitations set on how far aircraft could fly.

Despite best efforts, hidden properties or incorrect performance predictions of any Cr(VI)-free systems that are ultimately introduced cannot be excluded, and remaining risks must be mitigated. Ultimately extensive qualification and validation testing (as described in section 3.1.2 below) is not equivalent to 50 years real-life experience with corrosion protection.

Service life and maintenance intervals of parts and assemblies

Wherever possible, A&D hardware is repaired rather than replaced. In addition to both time and cost considerations, this is a much more environmentally friendly approach from a lifecycle perspective, resulting in reduction of hazardous chemical usage, energy usage, carbon footprint, waste generation, etc. In order to maintain operational safety therefore, A&D components and products are subject to intensive MRO activities.

For aircraft, there are different maintenance activities foreseen after defined intervals of flight hours or take-off or landing cycles:

- Prior to each flight a "walk-around" visual check of the aircraft exterior and engines is completed;
- A-checks entail a detailed check of aircraft and engine interior, services and lubrication of moving systems;
- B-checks involve torque tests as well as internal checks and testing of flight controls;
- In C-checks a detailed inspection and repair programme on aircraft engines and systems is undertaken.
- D-checks include major structural inspections with attention to fatigue damage, corrosion, etc. result in the aircraft being dismantled, repaired and rebuilt.

As an example, for commercial aircraft the A-checks occur every 400-600 flight hours, the B-checks are performed every 6-8 months, and the C-checks are completed every 20-24 months. C-checks typically take up to 6,000 man-hours to complete. The D-checks are completed every 6-10 years and typically take up to 50,000 man-hours to complete. At Lufthansa, the D-check begins with the stripping of the exterior paintwork. The aircraft is taken apart and each /system is checked thoroughly using the most modern methods for non-destructive material testing such as X-rays, eddy current probes and magnetic field checks. After several weeks and thousands of hours of intensive MRO work, the aircraft is overhauled completely. The D-check is the most extensive check foreseen for aircraft. Even at the D-check, certain areas of the aircraft, such as bonded structures and inaccessible regions, cannot typically be disassembled for inspection. Corrosion protection of these regions must therefore be sufficiently robust to last throughout the life of the aircraft.

The aerospace industry has a permanent learning loop of significant events, failure analysis and decisions for safety improvements. Part of this improvement is the introduction of the Maintenance Steering Group 3 Analyse (MSG-3), specifically developed for corrosion. MSG-3 provides a system for

OEMs and the regulators to identify the frequency of inspection with respect to the stress corrosion, protection and environmental ratings for any component or system. Without long-term experience the performance of a system cannot be highly rated due to hidden properties which may only be identified when extensive knowledge of in-service behaviour is available. The consequence of this is that the introduction of a Cr-free system would lead to a significant reduction in the maintenance interval, potentially doubling the frequency of the checks described above (GCCA, 2017).

3.1.2 Overview of the substitution process in Aerospace & Defence (A&D)

3.1.2.1 Introduction

Aerospace and Defence (A&D) products operate in highly challenging, extreme environments over extended timeframes. Due to these challenges, alongside engineering-based solutions, the A&D industry must use numerous high-performance mixtures which have passed through an extensive approval process in order to demonstrate their suitability for use – some of these mixtures will contain substances which are included on Annex XIV of REACH. Whilst substitution of substances of very high concern (SVHC) is a priority for the sector, and there have been extensive efforts to eliminate Cr(VI) and other SVHC wherever technically feasible, changes to A&D components offer unique challenges that are not seen in other industries. These include: the industry's dependence on certain SVHC to meet key safety requirements; the level of qualification and regulatory controls associated with introduction of alternative chemicals or other design changes; and the complexity of supply chains and the number of stakeholders involved in the substitution process.

In the civil aviation sector of the Aerospace industry, large numbers of aircraft **safely carry billions of people every year**[14]**,** whilst defence aircraft and systems are required to operate safely and reliably for 40 to more than 90 years before they are finally taken out of service**.** This requires A&D components to successfully fulfil a wide range of extremely challenging safety-related requirements, including but not limited to:

- High utilisation rate (around 16 hours per day for commercial aircraft, whilst critical defence systems must operate continuously for extended periods);
- Environmental and service temperatures ranging from below minus 55°C at cruising altitude to in excess of plus 200°C (Depending on substrate and location on final product);
- Wide ranging and varying humidity and pressure;
- High and varying loads;
- Fatigue resistance under varying modes of stress;
- Corrosive and abrasive environments (e.g., salt water and vapour, sand and grit, and exposure to harsh fluids such as cleaning solutions, de-icer, fuels, lubricants, and hydraulic fluids at in-service temperatures); and
- Maintained performance in the possible case of a lightning, bird, or other foreign object strike.

Successful, reliable, and safe performance against these parameters is the result of decades of experience and research, and a high level of confidence in the systems currently employed to provide corrosion and wear resistance. Years of performance data, as well as thorough reviews following any incidents, have resulted in improvements to the designs, manufacturing or maintenance processes employed in the industry. Such a level of confidence in the performance of Cr(VI) is essential as the treatments on some A&D components cannot be inspected, repaired, or replaced during the life of

[14] 4.5bn passengers carried and 38.3m departures in 2019. https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx

the A&D system. An inadequately performing surface treatment allows corrosion pits to form. These can turn into fatigue cracks, which potentially endanger the final product.

The civil aviation industry must comply with the airworthiness requirements derived from Regulation(EC)No 2018/1139[15] in the European Economic Area (EAA). Similar airworthiness requirements exist in all countries where aeronautical products are sold. These regulations require a systematic and rigorous framework to be in place to qualify all materials and processes to meet stringent safety requirements that are subject to independent certification and approval through the European Aviation Safety Authority (EASA), and other agencies requirements. Safety critical defence aviation and space systems are subject to similar rigorous performance requirements as seen in the civil aviation sector, while ground and sea-based defence systems are managed more adaptively based on specific system requirements.

Identification and implementation of feasible, suitable, and available alternatives in the A&D industry is a time consuming and complex process that can involve multiple stages of performance testing in laboratory trials, manufacturing trials and during inflight/in operation testing. Once a proposed candidate is identified, it must be shown that implementing it will maintain the stringent safety requirements that govern the sector. Not only this but, due to the potential implications of inadequate corrosion and abrasion protection described above, it must be ensured that the test candidate demonstrates equivalence in performance on all types of components where the original formulation/process is used. This can often be hundreds of different components, each requiring testing to ensure performance of the test candidate is acceptable.

The A&D companies that design and integrate the final product (e.g. aircraft, engines, radar, and other defence systems), are each responsible for their own product qualification, validation, and certification, according to airworthiness regulations or defence/space customer requirements. Even superficially similar components, when used in different systems or under different environmental conditions, may have unique design parameters and performance requirements, driven by the requirements of the final product. Consequently, an alternative that has successfully been implemented for one component in a given subsystem will not necessarily be suitable for use in a different subsystem. Implementation of an alternative in varying scenarios of use must be individually assessed, validated, and certified across the components, subsystems and systems that make up the final product, for example an engine, aeroplane, helicopter, missile, or tank (as illustrated in **Figure 3-1**).

Defence OEMs have additional challenges because individual defence customers usually assume full design/change authority upon accepting the defence hardware designs. This means that any intent to change the hardware configuration, including coatings and surface treatments, must be approved by the defence agency, who are concerned with the efficacy of the hardware (i.e. mission effectiveness) as well as meeting legislative goals, and can be very fiscally constrained for such hardware configuration updates. Alternatively, an OEM can attempt to persuade their customers of such hardware changes, but typically are not allowed to spend programme budgets on these hardware changes until expressly directed/contracted by the customer, who again are very fiscally constrained. When OEMs sell the same hardware to multiple defence customers, it is often required to obtain permission from each customer prior to hardware changes and these customers rarely agree. The combination of (a) not mission essential, (b) fiscal constraints, and (c) multiple conflicting customer opinions, greatly complicates any defence OEM effort to make hardware changes to existing designs to meet legislated goals such as chrome elimination.

[15] Repealing Regulation (EC) No 216/2008

The processes described apply to the implementation of any new design, or changes to an existing design whether still in production or not. This means, to ensure and maintain airworthiness and operational safety standards, they apply to every component produced for use in an aircraft or defence system. In the case of introducing Cr(VI)-free surface treatments, hundreds of individual components in each final product will be affected.

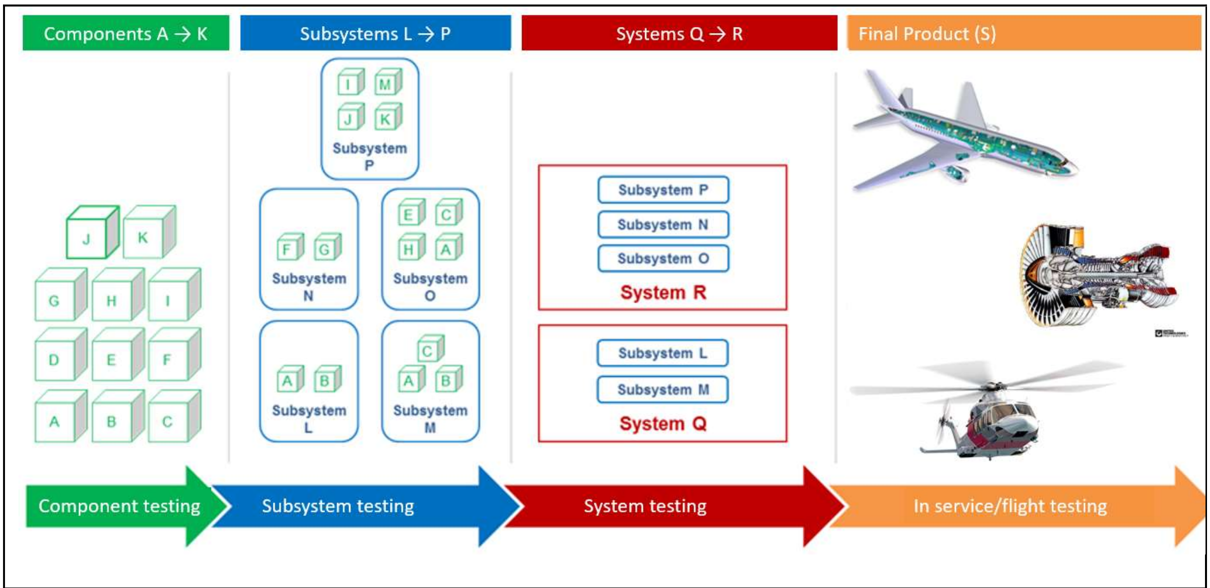

Figure 3-1: Assessment requirements in the implementation of alternatives
Source: Adapted from GCCA white paper

In the substitution process, many ADCR Consortium members use the Technology Readiness Level (TRL) scale as developed by the US National Aeronautics and Space Administration (NASA), and further defined by the US Department of Defence. This scale is used to assess the maturity level of each individual technology, and hence the potential suitability of a test candidate. The scale ranges from TRL 1, basic principles observed, to TRL 9, actual system proven.

Table 3-2: Technology Readiness Levels as defined by US Department of Defence

TRL	Definition	Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard[a] validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.

Table 3-2: Technology Readiness Levels as defined by US Department of Defence		
TRL	**Definition**	**Description**
5	Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system through successful mission[b] operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.
[a] Breadboard: integrated components, typically configured for laboratory use, that provide a representation of a system/subsystem. Used to determine concept feasibility and to develop technical data. [b] Mission: the role that an aircraft (or system) is designed to play. *Source: U.S. Department of Defence, April 2011, https://www.ncbi.nlm.nih.gov/books/NBK201356/*		

The TRL assessment guides engineers and management in deciding when a test candidate (be it a material or process) is ready to advance to the next level. Early in the substitution process, technical experts establish basic criteria and deliverables required to proceed from one level to the next. As the technology matures, additional stakeholders become involved, and the criteria are refined based on the relevant design parameters. A formal gate review process has been established by some companies to control passage between certain levels in the process.

Similarly, the maturity of manufacturing processes is formally tracked using the Manufacturing Readiness Levels (MRL) process. MRLs are used to assess the maturity of a given component, subsystem, or system from a manufacturing process.

Table 3-3: Manufacturing Readiness Levels as defined by US Department of Defence		
MRL	**Definition**	**Description**
1	Basic Manufacturing Implications Identified	Basic research expands scientific principles that may have manufacturing implications. The focus is on a high-level assessment of manufacturing opportunities. The research is unfettered.
2	Manufacturing Concepts Identified	This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined military needs.

Table 3-3: Manufacturing Readiness Levels as defined by US Department of Defence		
MRL	**Definition**	**Description**
3	Manufacturing Proof of Concept Developed	This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.
4	Capability to produce the technology in a laboratory environment	This level of readiness acts as an exit criterion for the MSA Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
5	Capability to produce prototype components in a production relevant environment	Mfg. strategy refined and integrated with Risk Management Plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling, and test equipment, as well as personnel skills have been demonstrated on components in a production-relevant environment, but many manufacturing processes and procedures are still in development.
6	Capability to produce a prototype system or subsystem in a production relevant environment	This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the EMD Phase of acquisition. Technologies should have matured to at least TRL 6. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself.
7	Capability to produce systems, subsystems, or components in a production representative environment	System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. Technologies should be on a path to achieve TRL 7.
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	The system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation.
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	The system, component, or item has been previously produced, is in production, or has successfully achieved low-rate initial production (LRIP). Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full-Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes.
10	Full Rate Production demonstrated and lean production practices in place	Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in full-rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level.

Table 3-3: Manufacturing Readiness Levels as defined by US Department of Defence		
MRL	Definition	Description
Source: Manufacturing Readiness Level (MRL) - AcqNotes		

Many companies combine the TRLs and MRLs in their maturity assessment criteria, as issues in either the technology or manufacturing development could affect production readiness and implementation of an alternative material/process. It should be noted that not all affected components in a system will necessarily attain the same TRL or MRL at the same time.

The process described above places limitations on the ability of the design owner, such as an original equipment manufacturer (OEM), to use "generic" commercially qualified components or "generic" commercially qualified formulations without extensive in-house testing. In general, such a component or formulation is unlikely to have been tested in a suitably qualified laboratory. The testing would need to cover all the design owner's specific configurations, involving all relevant substrates, and to consider interactions with all relevant chemicals including, but not limited to, paints, solvents, degreasers, de-icers, hydraulic fluids, and oils. There will also be specific testing required by a design owner in specific configurations which the producer of the component or formulator is not able to test.

The following section summarises the multi-step, multi-party processes that must be completed to develop test candidates and implement a Cr(VI)-free alternative into the supply chain, whilst highlighting the anticipated time necessary to complete these highly regulated processes. It should be noted that many ADCR members have multiple projects with the aim of developing and industrialising Cr(VI)-free alternatives running in parallel, as hexavalent chromates are used in a number of steps in surface treatment processes. Whilst the proposed candidates will be different for each use, taking into account the different requirements of the existing materials, the highly specialised individual experts at both formulator and design owner, and the required testing facilities, will be common. The competing priorities, and the capacity and specialised resource constraints, created by the need to substitute multiple chromates to the same timeframe will therefore also have a negative impact on the timeframes usually associated with the substitution process.

3.1.2.2 Process, requirements, and timeframe

Identification & Assessment of need for substitution

When a substance currently used in the production of A&D components is targeted for regulatory action and needs to be replaced, a component design change may be triggered. Completely removing a substance from one component may impact upon multiple other components and systems, and involve many different processes with varying performance requirements.

The first step is to identify extent to which the substance, or the formulation containing the substance, is used. This must consider the entire life cycle of components containing the substance throughout the supply chain, including maintenance, repair, and overhaul (MRO) activities. After identifying the relevant formulations, processes, and design references, the affected component designs and related systems are identified. This is the first step to assess the impact of substituting the substance and the scale of the design changes which may be needed.

The above work requires contributions from numerous personnel from various departments including Materials & Processes, Research & Development, Design & Definition, Engineering, Customer Service, Procurement, Manufacturing, Supply Chain, and Certification. Assembling this multi-disciplinary team and co-ordinating their activity is itself a complex and time-consuming activity.

Components on which Cr(VI)-based surface treatments are currently used may have been designed 30 to 40 years ago (or more), using design methods and tools that are no longer in use. Attempting to determine the potential interactions/incompatibilities of a Cr(VI)-free formulation or surface treatment process in an old design can take a tremendous amount of work. Failing to adequately identify all interactions creates a significant risk, whilst resolving any incompatibilities between old and new treatment materials and/or techniques is time intensive and has a high chance of failure.

When an existing design specifies a formulation or process utilising Cr(VI), the design change must not only comply with the performance requirements of the newly introduced components, but also be compatible and seamlessly interact with remaining legacy designs. This is because maintenance may require a Cr(VI)-free alternative to be applied proximal to the legacy formulation, containing Cr(VI). If the re-design is going to be integrated with old components treated with Cr(VI), compatibility must be assured.

Definition of requirements

Once a project seeking to develop and industrialise an alternative is launched, materials and process specialists from engineering, manufacturing, procurement, and MRO departments at the design owner, define the requirements that the proposed candidate must fulfil in order to be a suitable test candidate.

Alternatives must satisfy numerous requirements. In many cases those identified introduce competing technical constraints and lead to complex test programmes. This can limit the evaluation of proposed candidates. Categories of technical requirements may include:

- Performance requirements (e.g., corrosion resistance, wear resistance, adhesion strength, and compatibility with other materials);
- Design requirements (e.g., compatibility of the component's geometric complexity with the coating technique);
- Industrial requirements (e.g., robustness, processability, and repeatability); and
- Environment, Health & Safety (EHS) requirements (e.g., is there an equivalent level of concern).

For some materials dozens of individual requirements may exist across these categories.

Definition of requirements itself can be complex and requires a significant timeframe. The complexity can be due to:

- The substitute exhibiting behaviours or interactions which are different to the original product. Where unexpected behaviour is seen, sufficient operational feedback to technically understand the phenomenon and refine the requirements is essential to ensure non-regression;
- Consolidating requirements from multiple customers and suppliers into an existing design;
- Evolution of EHS regulations; and
- Need to substitute multiple chromates to the same timeframe.

Development of initial requirements can take at least six months, although requirements may be added and continue to be refined during the different levels of maturity, based on learnings from the various testing/qualification stages.

Key phases of the substitution process

Once initial technical requirements are defined, test candidates can then be identified and tested by the design owner. **Figure 3-2**, revised from the Global Chromates Consortium for Aerospace (GCCA) Authorisation applications, shows a schematic of the various stages in the process, which are described further below. These steps are not simply performed one after the other or presented in a chronological order, but rather they represent an iterative process.

Each stage in the process comprises various steps including extensive laboratory testing programmes and, in some situations, in service/flight testing. Each step therefore requires flexibility in the time to be completed, typically taking years overall. It should be noted that there can be **failures at any stage in this process**, and failures may not reveal themselves until a large amount of testing, taking considerable time and incurring significant expense, has already been carried out. Such failures result in the need to return to earlier steps in the process and repeat the extensive testing and associated activities leading to industrialisation. The later in the process these failures occur, the greater the impact will be on schedule and cost.

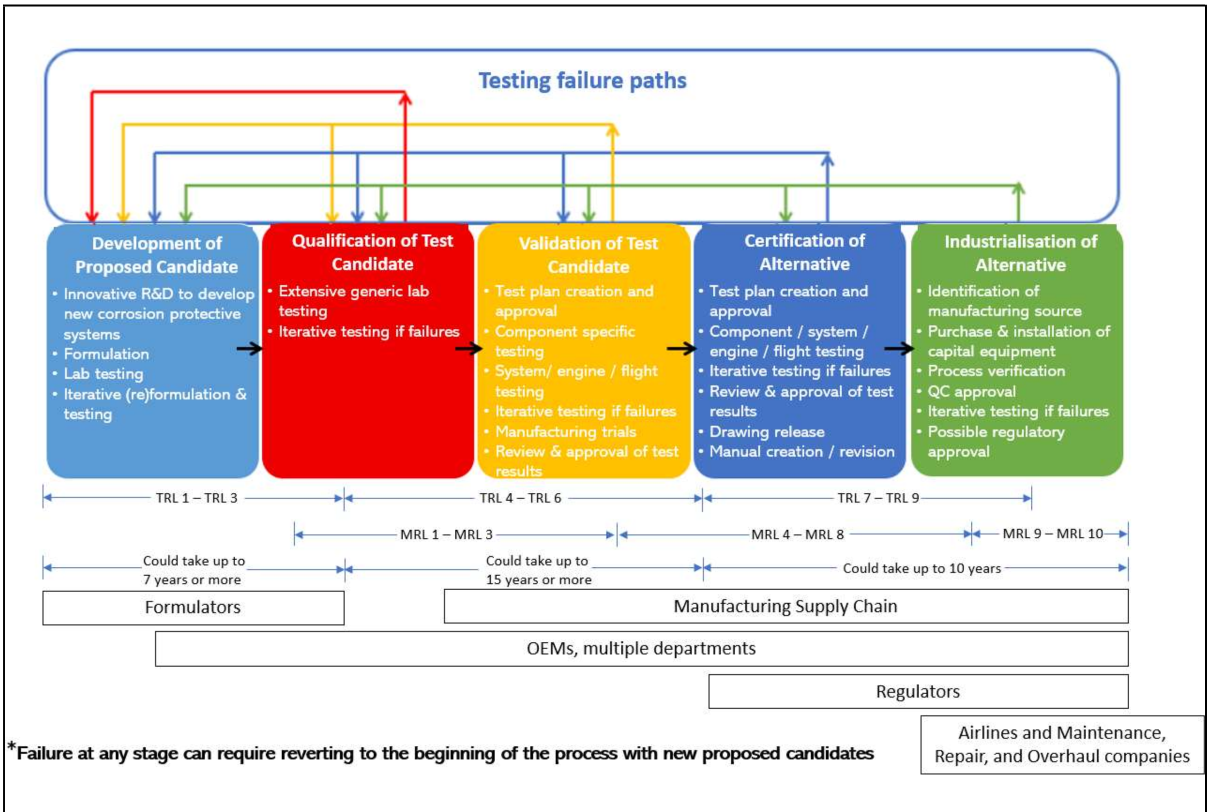

Figure 3-2: Schematic showing the key phases of the substitution process
Typical TRLs and MRLs associated with each stage, and the entities involved in each stage, are also shown. Note that failure of a proposed candidate at any stage can result in a return to a preceding stage including TRL 1. Note that failures may not become apparent until a late stage in the process.
Source: Adapted from "Use of strontium chromate in primers applied by aerospace and defence companies and their associated supply chains, Application for Authorisation 0117-01, GCCA (2017)

The detailed process involved in each phase of the substitution process is described below, and the associated timeframes are elaborated. Throughout the process it should be remembered that the initial qualification, validation, and certification of a final product is applicable to a single specific configuration of components and materials, assembled by a single set of manufacturing processes.

Any change to the components, materials, or manufacturing processes invalidates this initial qualification and certification. The action to approve and industrialise the change can only proceed once a suitable test candidate is developed, qualified, and validated.

Development of proposed candidates

When a need to develop an alternative has been identified (for example, as in this case, because of regulatory action driving the need to make an informed substitution), the first stage comprises innovative R&D, most commonly by the formulator(s), to develop new formulations. Initial activities in the development of proposed candidates stage include:

- Innovative R&D to develop new surface treatments;
- Formulation of proposed candidates;
- Laboratory testing of proposed candidates; and
- Iterative re-formulation and testing.

The development of proposed candidates must take into consideration the complex design parameters identified in the requirements development step discussed above. Once a proposed candidate is developed, testing is carried out in the formulator's laboratory to assess quantitative performance of the new formulation against the critical criteria required by the design owner. Failure against any of these criteria may result in rejection of the proposed candidate, further modification of the formulation, or additional testing. Although it may only be the Cr(VI) compound within a mixture which is subject to regulatory action, the other constituents may also require substantial change to continue to meet the stated performance requirements.

Formulators perform screening tests on small test pieces of substrate. Such tests provide an indication of whether basic performance criteria have been met, in order to justify more extensive testing by the design owner. The predictive power of laboratory tests performed by the formulators is limited and therefore it is vital to note that a formulation that passes these screening tests is not necessarily one that will be technically suitable to ultimately be fully implemented in the supply chain. **Passing these initial tests is a *necessary, but not sufficient***, pre-requisite for further progression through the process (i.e. a building blocks approach is followed).

Development typically involves an iterative process of re-formulation and re-testing to identify one or more proposed candidate. It is important to note that many iterations of these formulas are rejected in the formulator's laboratory and do not proceed to evaluation by the design owner. Formulators estimate that it typically takes two to five years of testing potential formulations before a proposed candidate is identified for submittal to the design owner[16].

Qualification of test candidate

Qualification is the first step in the process under which a design owner begins to verify that the treatment which may ultimately replace the Cr(VI)-based surface treatment has met or exceeded the specific performance criteria defined at the beginning of the substitution process.

Qualification applies to materials, manufacturing processes, and components, and comprises:

- Extensive generic laboratory testing; and

[16] GCCA

- Iterative testing if failures occur.

Once proposed candidates are developed by the formulator, the design owner evaluates the formulations by first performing their own screening tests. If the test candidate fails, formulators may choose to reformulate. It is common to iterate multiple times before a test candidate passes the design owners' screening, potentially adding several years to the substitution process (see **Figure 3-2** above).

For those test candidates which pass initial screening, additional testing is performed. Each company has explicit performance requirements, test methods, acceptance testing, and other characteristics for each component that are based upon the results of research, development, and prior product experience. This phase of the substitution process can take multiple years depending upon the performance requirements and only successfully qualified test candidates can progress to the validation stage described below.

Validation of test candidate

After a test candidate is qualified, the performance of each particular aerospace or defence use is validated based on its specific design criteria.

Validation is carried out on each relevant component, followed by system-level testing and engine/flight testing (if relevant). The activities in this stage can overlap with some of those that are carried out in the Certification stage and include:

- Test plan creation and approval;
- Component specific testing;
- Iterative testing if failures occur;
- System/engine/flight testing;
- Manufacturing trials; and
- Review and approval of test results.

The testing criteria are determined on a case-by-case basis with due regard to the design and performance requirements of each component and system. Testing in a relevant environment over an appropriate timescale is necessary, and therefore the validation stage may require full engine and aircraft flight tests, even for very low volumes of product. In the validation of manufacturing processes, the process robustness is also a vital aspect to be demonstrated at this stage.

Validation is carried out by the aerospace and defence companies, sometimes in collaboration with the manufacturing supply chain (in the Certification stage, the Regulator is also involved). Only the original design owner can determine when a test candidate is fully validated.

Some of the components impacted by the substitution of a surface treatment may form part of systems which are no longer in production. In order to conduct the testing required to validate the change on these components, it may therefore be necessary to build bespoke test hardware. Sourcing the relevant hardware and test equipment, and finding test facilities to do this, can add significant time to the process, whilst some of the testing performed at this stage will also be destructive, so failures can result in further schedule slippage. Together the Qualification and Validation processes encompass testing of the test candidate and can take more than 15 years to complete for the most challenging substitutions. At the end of the validation stage the removal of Cr(VI) from the production process is formally approved by the design owner.

Certification of alternative

Certification is the stage under which the component onto which the test candidate will be applied is certified by the Regulator or relevant authority as compliant with safety, performance, environmental (noise and emission) and other identified requirements. OEM's work with the certification authorities to develop a comprehensive plan to demonstrate that the aircraft, engine, propeller, radar system, munitions or any other final product complies with the airworthiness regulation or defence/space customer requirements. This activity begins during the initial design phase and addresses the final product in normal and specific failure conditions. The airworthiness regulations set performance criteria to be met, although they do not specify materials or substances to be used.

Steps in the Certification stage include:

- Test plan creation and approval;
- Component/system/engine/flight testing;
- Iterative testing if failures occur;
- Review and approval of test results;
- Drawing release; and
- Maintenance manual creation/revision.

For the civil aviation industry, the output of the original certification process is a Type Certificate, issued by the airworthiness authority (e.g. EASA) and granted to the engine, propeller, and airframe OEM. This is issued for the original design of the final product, rather than for each individual component, however every component of the final product must be designed, developed, and validated as meeting the requirements of the overall product and system design. The overall compliance demonstration for a new Type Certificate therefore may cover several thousand individual test plans, of which some will require several years to complete. This interconnection is illustrated using the example of an aircraft in **Figure 3-3** below.

Certification therefore applies to all components, sub-systems, and systems. A change to one individual component can affect the entire assembly of which it is a part (which may contain hundreds of components), and in turn the sub-system and system. Approval of the impacted components is granted after the airworthiness certification criteria, compliance standards/requirements and methods of compliance have been successfully demonstrated for those components, to the relevant Airworthiness Authority. The same process applies to defence products and systems, with the only distinction being how acceptable means of compliance are defined, and the certification authority (which will usually be a Ministry of Defence (MoD)). In the case of dual use aircraft (A civil and a military version of the same aircraft), or in the case of military specific aircraft, certification may need to be granted by multiple authorities (e.g. certification by the MoD could apply in addition to the EASA certification).

Removing a material or process reliant upon Cr(VI) and implementing an alternative is particularly challenging as it will involve in service or in production components. Re-certification of all components incorporating the new processes and materials is therefore required. As discussed in the description of the certification process in the GCCA AfA for strontium chromate[17], each of these components will need to be approved individually:

[17] Application for Authorisation 0117-01 section 5.3 available at b61428e5-e0d2-93e7-6740-2600bb3429a3 (europa.eu) accessed 06 June 2022

"Importantly, even if an alternative is in use in one component in aerospace[18] system A, it cannot be inserted into what appears to be the same part [component] in another aerospace system B (e.g., model B) until it is fully reviewed/validated/certified to ensure that either the design parameters are identical or that the alternative is fully acceptable for the different design parameters. Extensive experience shows that an alternative that is successfully certified in one component in one model cannot necessarily be successfully certified in another. In other words, the circumstances for each component in each model are unique and extrapolation is impossible without validation and certification."

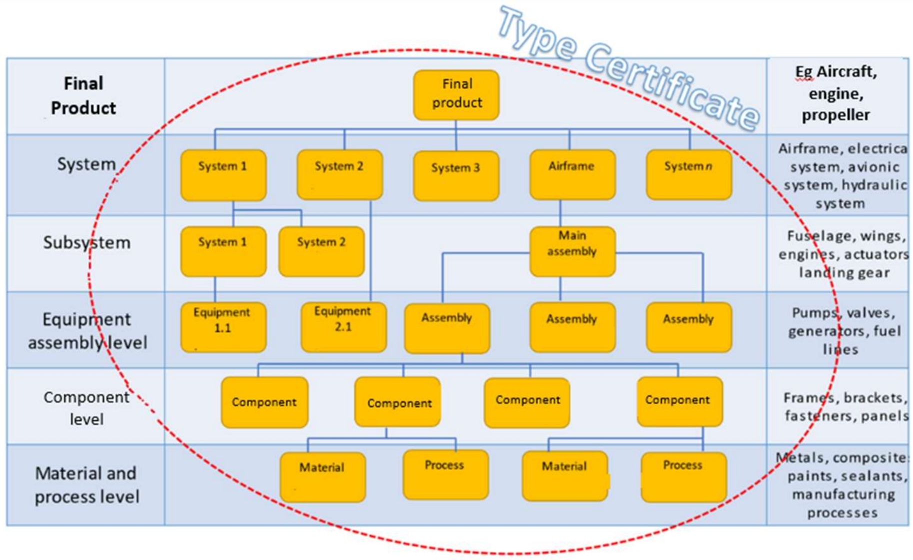

Figure 3-3: System hierarchy of a final product, showing the interconnection of each level in the system hierarchy, and how changes at a lower level have impacts on higher levels
Source: ADCR Member

After the alternative is certified, design drawings and part lists need to be revised to put the requirements of the Cr(VI)-free material/process as an alternative to the legacy requirements. Thousands of components could be impacted by each process. Only once these revised design drawings have been released can industrialisation of the alternative begin.

Over their operational life A&D components are exposed to extreme mechanical forces and environmental conditions which affect their performance. In order to continue to meet requirements, and ensure operational safety, A&D components and products are therefore subject to intensive MRO activities. The strict schedule of the maintenance program, and method for repair, is stated in the maintenance manual and must be officially approved. For most A&D organisations, repair approval is distinct from design approval, although the processes are analogous and may be undertaken concurrently. Once repair approval is complete the alternative will be included in maintenance manuals.

During initial manufacture, all the components of the system are in a pristine and relatively clean condition, whereas during repair and maintenance, the components are likely to be contaminated and suffering from some degree of (acceptable) degradation. Furthermore, certain cleaning and surface preparation techniques that are readily applicable during initial manufacture may not be available or practical during repair and maintenance. Carrying out MRO activities on in-service products is further

[18] In this parent dossier, the term aerospace is defined as comprising the civil aviation, defence/security and space industries.

complicated due to restricted access to some components, which are much more readily accessible during initial manufacture and assembly. These factors are significant with respect to surface treatments, as their performance is strongly dependent upon the condition of the surfaces to which they are applied. As such, all these conditions must be addressed in the repair approval process.

The certification and industrialisation stages (see below) encompass progression of the alternative from TRL 7 to TRL 9 and together these stages can take six to ten years to complete. In certain defence applications, certification alone can take more than ten years.

Industrialisation of alternative

Industrialisation follows the certification of the component design incorporating the alternative and is an extensive step-by-step methodology followed to implement the certified material or process throughout manufacturing, supply chain and MRO operations, leading to the manufacturing certification of the final product.

Elements of the Industrialisation of alternative process include:

- Identification of potential manufacturing sources;
- Purchase and installation of manufacturing equipment;
- Process verification (Due to the fact that the industry is working on special processes, the supply chain must be qualified);
- Quality Control (QC) approval; and
- Regulatory approval if needed.

A&D products consist of up to a million components provided by thousands of suppliers or manufactured internally by OEMs, making communication between OEMs and their supply chain regarding what is permissible for use on A&D products key. Suppliers must be vetted through a supplier qualification process prior to being issued a contract. This process typically involves internal approval, contract negotiation, running a specific qualification test program, and undertaking an audit on potential risks of working with a supplier. A supplier may be requested to sign a manual or code of conduct by the OEM, to ensure expectations for work and awareness of required standards is achieved. Once the supplier is qualified, periodic audits are performed to ensure continued compliance with contractual requirements. Significant investment, worker training and manufacturing documentation may be required to adapt the manufacturing processes for new alternatives, which sometimes require changes in existing facilities, the construction of new facilities, or switching to a different facility (including a different supplier's facility).

The industrial implementation is usually scheduled to follow a stepwise approach to minimise the technical risks, and benefit from lessons learned. This implies that the replacement is not implemented simultaneously in all plants and at all suppliers but instead often uses a stepwise approach. Each OEM may operate dozens of manufacturing sites/final assembly lines worldwide.

For components already in products, long-term contractual agreements are often already in place with suppliers. When a change is made to a drawing to incorporate a new alternative, the contract with the supplier needs to be renegotiated, and additional costs are incurred by the supplier when modifying and/or introducing a new production process. These may include purchase and installation of new equipment, training of staff, internal qualification of the new process, OEM qualification of the supplier, manufacturing certification of the supplier, etc. In addition, the supplier may need to retain the ability to use the old surface treatment, or qualify different solutions for different customers/components, which requires the supplier maintain parallel process lines to accommodate multiple surface treatments/processes. The level of complexity varies by component and process. In some cases, the supplier may be sub-contracting the process. In addition to production organisation approval, the approval of maintenance organisations is also required. This means multiple layers of activity in the industrialisation process.

The industrialisation of alternatives is constrained by many factors including: the complexity of supply chains; extent of process changes required; and the airworthiness regulations or defence/space customer requirements. Even simple changes can take up to five years. When more than one alternative process is introduced simultaneously, up to a decade or more may be necessary for full implementation of the alternative.

The industrialisation process includes the creation and approval of process documents or manufacturing/repair documents. These documents allow detailed implementation of the manufacture and/or repair of each component.

Using the example of a commercial aircraft, a simplified example of the process, described above and leading to industrialisation of the alternative, is illustrated in **Figure 3-4** below.

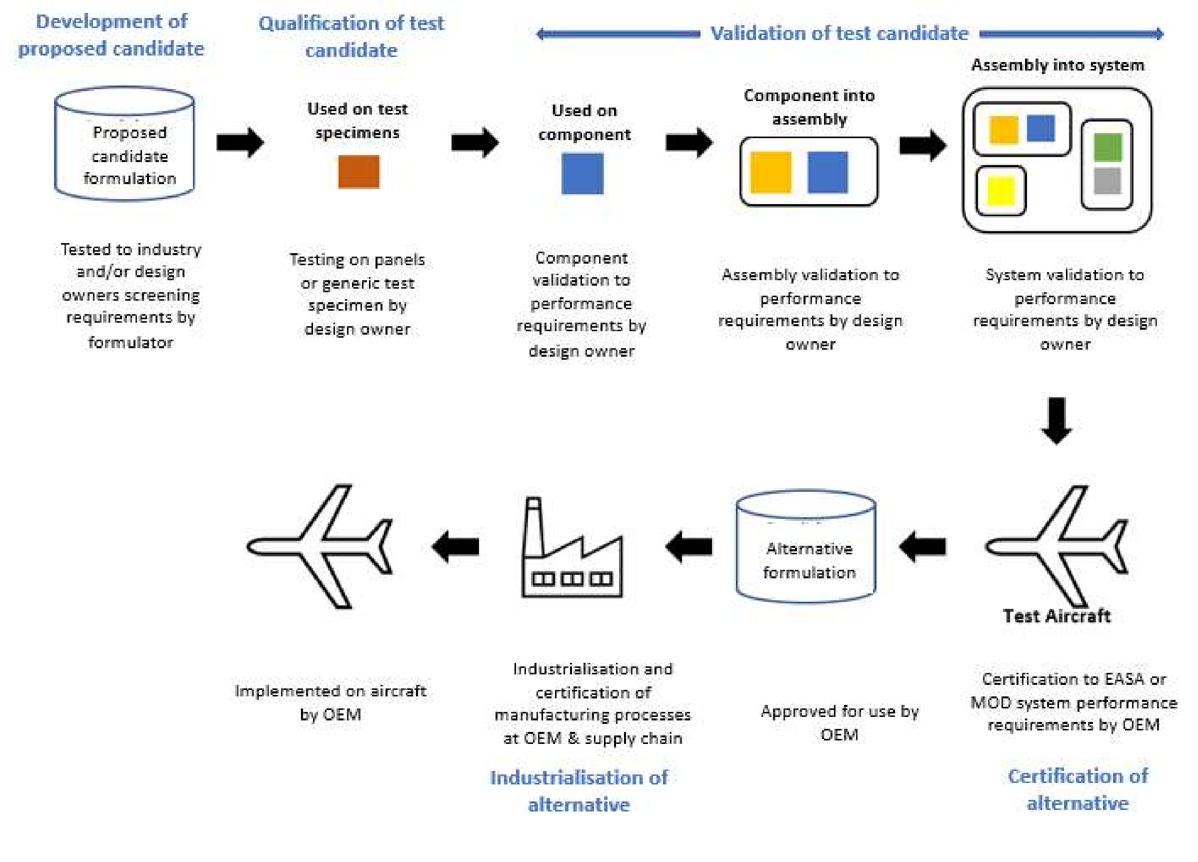

Figure 3-4: Process to Certify a Formulation for use on Aircraft
Formulations used in production have completed this process. New or reformulations must follow same process for use in production.
Source: ADCR Member

3.2 Description of the functions of the chromates and performance requirements of associated products

3.2.1 Technical feasibility criteria for the role of the chromates in electroplating

3.2.1.1 Introduction

The development of technical feasibility criteria for proposed candidates to replace the use of chromium trioxide in electroplating has been based on a combination of; assessment of the parent AfAs, consultation with ADCR Consortium members, and a review of available scientific literature.

Using detailed written questionnaires (disseminated throughout 2021 and 2022) the ADCR Consortium members were asked to review the technical feasibility criteria and provide details of the technical performance criteria which Cr(VI) meets in this use and that any alternatives (substances and technologies) would also need to meet before they are seriously considered as possible replacements.

In parallel, scientific literature delving into specificities of electroplating and the assessment of the technical feasibility of specific alternatives was collected and analysed (with the assistance of the ADCR members) and has been incorporated into the analysis.

The technical feasibility criteria that shall be used in the assessment of selected alternatives are as follows:

- Wear resistance;
- Hardness;
- Layer thickness;
- Corrosion resistance;
- Coefficient of friction; and
- Effect on surface morphology.

As noted above, this combined AoA/SEA covers the use of one chromate for electroplating; chromium trioxide (including "acids generated from chromium trioxide and their oligomers", when used in aqueous solutions).

In the context of technical feasibility, it is important to note that the mode of action for each of the technical feasibility criteria clearly describes the contribution of the Cr(VI) species in the delivery of electroplating. By extension, the donor chromate substance containing Cr(VI) (i.e., chromium trioxide) is responsible for delivering the functions attributed to Cr(VI) within electroplating. As such, the discussion of the technical feasibility and the functions imparted by electroplating encompasses the mode of action by which the Cr(VI) delivers these functions.

It was noted by some of the members that, in addition to the technical feasibility criteria described below, other important functionalities are required to be met in some cases. For example, it is important for one company's customers that the chrome plating has adequate UV resistance, as in the case of insufficient UV resistance on the plating, a colour change from black to grey/white may be observed, which is not accepted by the customer as it may indicate chemical degradation of the coating. For components such as aircraft windshield wipers, the risk is that it could affect the sight of the pilot, which is indeed unacceptable.

Additional properties that were reported by members include the ability of the coating to obtain the correct dimensions, geometry and surface finish, fatigue debit on the base alloy, and chemical resistance.

3.2.1.2 Role of standards and specifications in the evaluation of technical feasibility criteria

At the development phase, as described in section 3.1.2, proposed candidates are at an early stage of evaluation represented by TRL 1-3, and not recognised as credible test candidates at this stage. These proposed candidates are screened against the technical feasibility criteria, or key functions impacted by the use electroplating. These functions are measured against performance thresholds using standardised methodologies. The performance thresholds are most often assigned by the design owner of the component subject to the treatment.

As stated, test methodologies are defined within standards and specifications. Standards may be within the public domain originating externally of the A&D sector from professional bodies (e.g. BSI or ISO). Specifications are often internal to the aerospace and/or defence company, or a Government Defence Department (MoD) with access to the documents controlled by the manufacturer and/or design owner of the component. As such, these documents are typically classified as confidential business information.

In the context of the AoA, the importance of the performance thresholds and standards are multi-fold; to ensure reproducibility of the testing methodology, define acceptable performance parameters and determine if the proposed candidate exhibits regression or is comparable in performance compared to the benchmark Cr(VI) substance.

The role of the specification is limited within the substitution process. It provides a reproducible means of screening proposed candidates, however, is typically unsuitable for more mature stages within the substitution process when proposed candidates transition to credible test candidates. These subsequent phases in the substitution process are subject to in-depth, often bespoke, testing as required within steps TRL 4-6 and above. Testing regimes to meet the requirements of TRL 4-6 often transition from simple specifications intended for quality control purposes, to evaluation of treated components/sub-assemblies via breadboard integrated components either within the laboratory or larger simulated operational environments. These advanced testing regimes rely upon the use of specialised equipment, facilities, and test methodologies such as rig tests or prototype systems, see **Figure 3-5**. Attempts to replicate environmental in-service conditions are built upon bespoke testing regimes developed over decades of Cr(VI) experience from laboratory scale test panels to test rigs housed in purpose-built facilities. However, they cannot always reproduce natural environmental variations, therefore there can be differences between what is observed in the laboratory and experienced in the field.

Figure 3-5: Multi-climate chamber for simulated environment testing
Source: Airbus SAS 2022

Examples of standards used for screening proposed candidates within the development phase of the substitution process are presented in **Table 8-1**. As stated above, standards serve to provide a means of reproducible testing within the development phase of the substitution process. Both standards and specifications are tools used to evaluate proposed candidates and identify suitable test candidates.

Interrelationship of technical feasibility criteria and impact on surface treatment "system"

When considering technical feasibility criteria, in many instances these are strongly interrelated in the delivery of the use, and it is not possible to consider one criterion independently of the others when assessing proposed alternatives. The individual criteria collectively constitute part of a "system" delivering the "use" with a degree of dependency on one another.

For example, the thickness of a chrome coating on a substrate can in turn affect the degree of corrosion protection instilled by the coating, as well as the wear resistance and flexibility of the coating. Hard chrome plating can be applied in a layer with a typical thickness range between 1.5µm and 1mm, however the potential thickness of the coating does not have a limit. The coating results in high mechanical and wear resistance, with a low coefficient of friction and a degree of corrosion protection.

Moreover, a coating system providing improved wear properties may significantly reduce the fatigue life of a component due to cracking of the coating penetrating into the substrate material (Bodger, Mcgrann and Somerville, no date). The resulting cracks may propagate through the substrate, resulting in loss of the component. Hard chrome plating can create a fatigue deficit, i.e., chrome plated components have shorter fatigue lives than uncoated components (Budinski, 1988).

3.2.1.3 Technical feasibility criterion 1: Wear resistance

The wear performance of hard chrome plate is a critical functionality in two respects; firstly, the surface finish created by hard chrome plate is a hard and wear resistant material that effectively protects substrate material against wear in service i.e. the hard chrome plate is sufficiently wear resistant that it remains in place and provides a physical barrier. Secondly, the hard chrome plate does not adversely affect mating parts that move relative to it, examples would be seals and bearings. In practical terms this means that contacting parts do not wear out unduly quickly as a chrome plated part moves back and forth in operation. The microcracked structure of the hard chrome plate contributes to this benefit by retaining lubricating fluids on an otherwise very finely finished surface. For many applications the above performance benefits are essential, proposed candidates for the replacement of Cr(VI) must provide equivalent performance to avoid unacceptable reductions in unit service lives.

The high wear and abrasion resistance is a result of various properties of the metallic chromium layer, including the hardness of the layer, the very low friction coefficient and adhesive strength of the metallic chromium, as well as the crack network perpendicular to the chromium layers. As noted above, the latter enhances the application of lubricants, which further enhances the wear and abrasion resistance properties of the coating (Richard E. Petty, 1994). The hard chrome deposits resist abrasion from lower hardness materials that can enter the wear zone as contaminants.

Wear resistance is generally tested via its sliding and abrasion resistance behaviours, however in the aerospace sector, reciprocating sliding wear testing against materials used as counterparts is more common. In the testing of weapon systems, the very aggressive chemical environment combined with high temperature and velocity, requires the use of reference-treated barrels for live firing tests.

One of the standard test measurements for wear resistance is the Taber abrasion test, carried out according to ASTM D4060. General requirements stated within the test for metallic chrome coating applications are < 50mg/10,000 cycles.

3.2.1.4 Technical feasibility criterion 2: Hardness

The hardness of the electrodeposited chrome plating is defined as the resistance of solid matter to various kinds of permanent shape changes when force is applied. The total hardness of the product is the combined result of the substrate hardness and coating hardness. The most common method of measuring the hardness of a metallic material is to measure the Vickers hardness (HV) according to ISO 6507, which can be applied across many industry sectors and has a minimum requirement of 700-900 HV for aerospace applications. Hardness is in turn related to the abrasion resistance of a material.

3.2.1.5 Technical feasibility criterion 3: Layer thickness

Layer thickness is a key function identified in the parent AfAs and confirmed by the ADCR members. The layer thickness depends on the specific application and requirements, and so can vary significantly between these applications. The layer thickness has a high impact on the properties of the final coating – thin deposits allow for a more flexible coating and reduce the risk of cracks, while thick deposits increase wear resistance and corrosion performance.

Typical layer thickness for electroplated chrome coatings in the aerospace sector can range from 1.5µm up to 1mm, depending on the application, while layer thickness for repair and restoration of worn aircraft components is often in excess of 100mm. Several non-destructive methods are available to measure layer thickness, including:

- Magnetic method, ISO 2178 and ASTM D7091;
- X-ray method, ISO 3497 and ASTM B 568;
- Coulometric method, ISO 2177; or
- Manual measurements using calipers, micrometers or other tools.

Layer thickness is of particular importance in those legacy parts where electroplating acts as a wear resistant surface (e.g. transmission shafts). Altering the layer thickness associated with the surface treatment would necessitate a full redesign of the component.

3.2.1.6 Technical feasibility criterion 4: Corrosion resistance

The terms corrosion resistance and corrosion protection can be used interchangeably, or to refer to two different properties possibly instilled within the same process. Corrosion protection can be provided by a physical barrier, such as the metallic chrome coating.

The microstructure of the hard chromium deposit is heavily influenced by the chemical constituents of the electrolyte present in the plating process, as well as the temperature, current density, level of agitation and several other variables in the electrodeposition process. The microstructure can be altered to be crack-free, macro-cracked or micro-cracked, depending on the application. The ductility of a crack-free coating is poor and often results in macro-cracking of the coating, which reduces corrosion resistance and promotes spalling[19]. However, micro-cracked hard chromium coatings are extremely useful and are influenced by the kinetics of plating, and the way hydrogen evolution is controlled in the process.

The microstructure of a chrome coating ranges from tight coatings with inner tension to tension-free coatings. The structure of the deposited chrome is a hexagonal crystal, which reorganises itself into tight body-centred cubic structures which free the built-up hydrogen. The micro-cracked structure reduces the overall corrosion resistance of the chromium plating, but this is countered with the application of the correct lubrication oils, which fill the micro-cracks and acts as a barrier to corrosive environments.

Chrome plated components such as those in landing gears can come into contact with all atmospheric components (e.g., moist air, NO_x, SO_x, radicals, ozone) if they are not further protected with fluids or lubricants, as the chromium layer displays a lower level of corrosion resistance compared to other Cr(VI)-based surface treatments, due to its sensitivity to acids. It is the additional layer thickness and more importantly the network of cracks on the surface of the coating combined with the addition of lubricants that provide enhanced corrosion resistance.

Corrosion protection is described by members as resulting from the barrier established by the hard chrome plating. Active corrosion resistance is not a result of the presence of Cr(VI) on the final coating, as there is no Cr(VI) present on the final coating.

Corrosion resistance is of particular importance for helicopters, which fly in very different environments and especially at low altitude over sea and ocean environments which can cause extreme corrosion. Corrosion protection is aided by the metallic chrome coating, which can be easily and naturally passivated, with the resulting layer thickness up to several 1/10 mm.

3.2.1.7 Technical feasibility criterion 5: Coefficient of friction

Friction is the force resisting the relative motion of solid surfaces sliding against each other. The friction coefficient is low for functional chrome plated surfaces, and can be determined by tribological testing according to ASTM D1894 (the standard test method for static and kinetic coefficients). The aerospace industry can, in the case of moving parts, require a lubricated friction coefficient of less

[19] Fragments of a material that are broken off from a larger solid body.

than 0.2. Low friction and tribological properties are a particular function especially required in the aerospace sector and are important in components such as the landing gear and hydraulic systems, as well as in shock absorbers. The friction properties of a hard chromium layer are a result of the very low friction coefficient accompanied by a crack network perpendicular to the layer. Both effects can be observed in chromium layers derived from Cr(VI) under electrochemical conditions.

3.2.1.8 Technical feasibility criterion 6: Effect on surface morphology

The defined surface texture of the substrate, which has been created during pre-treatment, must be kept during the plating process. In this defined surface morphology, a certain amount of oil can be retained for lubrication. The ideal surface roughness varies for different applications in the range of 0.7µm to 15µm.

The chromium deposit provides surface roughness in the application range as required, perfectly following the surface during electroplating. Only chromates have the property for depositing in hemispherical structures during coating. The number, size, distribution, coverage, and other structural parameters of these hemispheres can be adjusted according to the application (Leimbach *et al.*, 2019).

The required surface roughness is achieved in different ways depending on the thickness of the coating. Any alternative to chrome plating which was to be universally applied would need to be able to achieve the desired surface finish when used in place of thin chrome plating, whilst also be capable of being ground to create the required surface roughness when used in place of thick chrome plating. This is one of many reasons that several different alternatives may need to be implemented within both the sector, and individual organisations, depending on the component to be treated.

3.3 Market analysis of downstream uses

The market analysis of downstream users is provided in section 4.2.

3.4 Efforts made to identify alternatives

3.4.1 Research and Development

3.4.1.1 Past Research

As highlighted throughout, the substitution of Cr(VI) substances in the aerospace and defence sector is met by particularly strong challenges. (Rowbotham and Fielding, 2016) highlight the nature of such challenges, noting that there are an estimated three million components in each of the 20,000+ aircraft in service. The demanding nature of service environments in the aerospace sector, and potential for serious consequences if only one component should fail, dictate that very stringent measures are adopted and enforced when developing and qualifying chromate alternatives.

Various R&D activities were reported within applications for authorisation relating to this Review Report for the use “electroplating/hard chrome plating”.

Alternatives identified in previous applications are summarised in **Table 3-4** below. These alternatives were evaluated in previous AfAs and are listed with the relevant application reference. The TRL assessment should be noted as a minimum, based on the alternatives’ implied, or stated, level of adoption at the time the AfAs were submitted; c. 2015.

Table 3-4: Electroplating summary of alternatives from previous AfAs				
Category[a]	**Alternative**	**TRL in 2015**	**Years to implement concept (from 2015)**	**AfA**
1	Electroless Nickel Plating	1[b]	> 15 years	0032-02
1	Nickel/nickel alloy electroplating	1[b]	> 15 years	0032-02
1	Case hardening: carburising, carbonitriding, cyaniding, nitriding, boronising	1[b]	> 15 years	0032-02
1	Chemical vapour deposition	2[b]	Minimum 10-15 years	0032-02
1	Nanocrystalline Cobalt Phosphorous alloy coating	Low	> 15 years	0032-02
1	High velocity thermal process (including high velocity oxy fuel (HVOF) and detonation gun (D-gun) processes)	1[b]	Minimum 10-15 years (0032-02)	0032-02 0044-02
1	Chromium (III) plating	Low	10-12 years provided technical criteria can be met	0032-02
1	Physical vapour deposition	1[b]	> 15 years	0032-02
2	Plasma spraying	6[b] specific components 1[b] general alternative	5 years for specific components > 15 years for a general alternative	0032-02
2	General laser and weld coating technology	1[b]	> 15 years	0032-02
2	Stainless steel and high-speed steel		> 15 years	0032-02
2	Thermal spray coatings	1[b]	> 15 years	0032-02

Notes:

(a) "Category" refers to level of development of each alternative at submission of the parent AfAs;
1. Relevant R&D ongoing at the time; 2. Discussed mainly in literature with limited suitability.
(b) The TRL is not stated and so has to be estimated based on the overview provided in the parent AfAs.

To further highlight the significant efforts being made by the aerospace and defence sector to substitute chromates, ongoing and past "R&D collaborations" are identified below. It is noted that collaborations are mentioned within the parent AfAs associated with the ADCR Consortium combined AOA/SEAs, e.g., the Global Chromates Consortium for Aerospace (GCCA), the chromium trioxide Authorisation Consortium (CTAC) and the chromium VI Compounds for Surface Treatment (CCST). However, this review focuses on recognised collaborations which include research into the development of alternatives for Cr(VI) electroplating and identify additional relevant collaborations.

A short summary of the collaborations relevant to chromium electroplating is provided below. Please note that for many projects, only limited information is publicly available due in part to maintaining intellectual property rights and potentially patentable technologies.

CTAC AoAs 0032-02, 0032-04, and 0032-05 all mention the Highly Innovative Technology Enablers for Aerospace (HITEA) programme, which was initiated in 2012. The AoAs note that HITEA phase one was completed in 2015. Two other HITEA programmes have been initiated since completion of the first project. Additionally, the HardAlt project, which is noted as further funding from a HITEA project involving the University of Southampton and the Technology Strategy Board. HardAlt was part funded by the European Union and considered an electroplating method using Nickel Phosphorous (Ni-P).

Relevant collaborations/projects include:

- **HITEA 1:** Seventeen stakeholders gained funding from Innovate UK (part of UK Research and Innovation[20]) through the HITEA programme for project: "REACh Compliant Hexavalent Chrome Replacement for Corrosion Protection". Other funding was gained through the EPSRC (Engineering and Physical Sciences Research Council). The initial project was funded between April 2013 and September 2015, with a total award of £695,588 received from Innovate UK. EPSRC funded three separate HITEA projects from April 2013 to 2015 as part of the first stage of HITEA research totalling £360,347 (UK Research and Innovation, 2021e, 2021f, 2021g, 2021h). The first HITEA project considered alternatives for hard chrome plating, among other uses.

- **HardAlt:** A new generation of protective coating alternatives to hard chrome was partially funded by the European Union project running from 1 December 2013 until 30 November 2016. The project aimed to develop a quick electroplating technique with a lower energy consumption using Ni-P coatings. HardAlt was a follow-on collaboration from the first HITEA project. Outcomes from HardAlt included:

  - A novel method for utilising pulse current regime in Ni-P electrodeposition;
  - Utilising pulse current regime in composite Ni-P electrodeposition;
  - Improved system of reinforcement particle dispersion in the plating bath;
  - Enhanced annealing of Ni-P coatings; and
  - Enhanced annealing of composite Ni-P coatings.

  The researchers state that the Ni-P coatings will ensure REACH compliance due to elimination of Cr(VI), as well as benefiting SMEs using electroplating processes. The coatings are suggested to be better for workers health and the environment, as well as cheaper, and better quality with an increased rate of deposition compared to conventional chromium-based electroplating. It is noted that raw material costs are higher, however this is said to be offset as overall production costs are lower.

- **Co-deposition of Ni-P alloys reinforced with boron carbide microparticles: direct and pulse plating:** Bernasconi, Allievi, Sadeghi & Magagnin (2017) considered Ni-P coatings reinforced with boron carbide particles electrodeposited with both direct current and pulse platings as a replacement for hexavalent chrome. The results of this study highlighted that plating from a high phosphorous content bath resulted in a greater overall phosphorus content in the coatings. When the coating was applied with the pulse method, the coating's phosphorus content was higher than when a direct current was used. This suggested that the co-deposition of phosphorous onto the Ni-P alloy is stabilised by the pulse plating method, enabling higher phosphorous content of the coating to be achieved. In addition, these thicker coatings were able to form using higher current densities and increasing boron carbide particle concentrations within the baths until a saturation point was reached. The microhardness of co-deposits was investigated and highlighted that pulse deposition generally resulted in higher levels of microhardness. It was also found that in high phosphate composites the content of Borcarbid 1500F had more of an impact on the achieved hardness than in low phosphorus composites. Overall, the low phosphate method appeared to show a greater degree of microhardness than the higher phosphate method, peaking at 830 HV and indicating NiP-B_4C coatings have a good level of microhardness for coating uses.

[20] A public body sponsored by the Department for Business, Energy and Industrial Strategy

- **Effect of annealing temperature on microstructure, mechanical and tribological properties of nano-SiC reinforced Ni-P coatings:** Wang et al, (2017) investigated the properties of nickel-phosphorous/silicon carbide (NiP/SiC) nanocomposite coatings when annealed at different temperatures between 350 and 500°C. Annealing at 500°C with large quantities of Ni_3P resulted in the lowest friction coefficient of 0.51 and wear rate of 7.8×10^{-6} mm^3/Nm. The authors stated that in terms of cost and performance, SiC reinforcing particles in an Ni-P matrix is the most effective means of strengthening Ni-P coatings.

- **Evolution of structural, mechanical and tribological properties of Ni-P/MWCNT coatings as a function of annealing temperature:** Wang et al., (2016) followed a method similar to the above, however considered nickel phosphorous/multi-walled carbon nanotube (Ni-P/MWCNT) coatings. Coatings annealed at less than 380°C were found to be less dense and subsequently have a higher wear rate of 2.9×10^{-5} – $3.0 \times 10^{-5}$$mm^3$/Nm. The coatings were heated in an electric furnace at a constant heating rate of 5°C per minute until the target temperature was reached. The temperature was held for an hour before cooling to room temperature. Results suggest that annealing at 400°C resulted in the lowest friction coefficient due to the H_3PO_4 acting as a lubricant. However, decomposition of amorphous carbon in MWCNTs which occurred optimally at temperatures below 380°C provided hardness and wear resistance.

- **ASETSDefence:** Advanced Surface Engineering Technologies for a Sustainable Defence (ASETSDefence) consists of the Strategic Environmental Research and Development Programme (SERDP) and the Environmental Security Technology Certification Programme (ESTCP) and is a US Department of Defence (DoD) initiative. ASETSDefence aim to provide information on environmentally friendly surface engineering technologies, including chrome-free alternatives. CTAC AoA 0032-02 notes ASETSDefence provide access to background information and the status of implementations and approvals to the public. The alternatives associated with hard chrome plating studied under the scope of the ASETSDefence project are listed below:

    - HVOF: WC-Co, WC-CoCr, Cr3C2-NiCr
    - Electroless Ni-P
    - Ion nitride (plasma nitride)
    - Ferritic nitrocarburizing
    - PVD CrN
    - PVD WC-C (diamond-like carbon with tungsten)

  HVOF is mentioned within the AoAs for 0032-02 (chromium trioxide) and 0044-02 (potassium dichromate) as an alternative to chromium electroplating. Electroless nickel-phosphorous is discussed within 0032-02 (chromium trioxide), as is case hardening, including carbonitriding, however no direct reference is made to ferritic nitrocarburizing. Physical vapour deposition (PVD) is covered in CTAC 0032-02 and 0032-05.

Table 3-5: Hard chrome plating alternatives	
Alternative	**Examples of industry approvals and applications**
HVOF WC-Co, WC-CoCr, Cr_3C_2.NiCr implementation	All new design military and civilian aircraft landing gear, various actuator components – piston rods, pins, F-35 landing gear, various actuator rods C-17 nose landing gear post shelf Numerous landing gear component repairs at OO-ALC Airline and aircraft MRO – landing gear, slat/flap tracks Various turbine engine components – FRC-E, FRC-SE, OC-ALC Ships, submarines: Large hydraulic rams, shafts for pumps, generators, turbines OEM and MRO of large vehicle hydraulic rods Numerous industrial valves, rolls, etc
HVOF WC-Co, WC-CoCr approvals	Approved by NAVAIR for P-3 landing gear Approved by Boeing for commercial landing gear MRO
Electroless Ni-P implementations	Various hydraulic cylinder internal diameters (aircraft landing gear)
Ion nitride (plasma nitride)	Corrosion service on some commercial actuators
Ferritic nitrocarburizing	Commercial hydraulics, including corrosion service
PVD CrN	Diesel engine piston rings (Japan)
PVD WC-C (diamond-like carbon with tungsten)	Diesel engine fuel injector rods Moulds, dies
Source: ASETSDefence	

- **Hard Chromium Alternatives Team (HCAT):** the HCAT is a collaboration between the US DoD and the Canadian DoD (SERDP and ESTCP) founded in 1996. As stated in CTAC AoA 0032-02, HCAT considered HVOF as an alternative to functional chrome plating for the aerospace industry and military usage. CTAC states that HCAT found HVOF to have temperatures and geometrical limitations and high costs.

Table 3-6: HCAT Summary of Alternatives and Uses			
Alternative	**Qualifications/In-test[(a)]**	**Applications**	**Limitations**
Thermal spray (HVOF)	Qualified	Landing gear, hydraulics, flap tracks	> 0.001” thick Not IDs
Electroless nickel (Ni-P, Ni-B)	Qualified	IDs, other NLOS, TDS alt. Compressor blades, shaft rebuilding, flap tracks, bearing journals	Adhesion, build-up, heat treat. May be subject to future regulation; regrettable substitution candidate
Nano Co-P electroplate	In test	IDs, TDC alt., carrier heat treat	Heat treat
Physical vapour deposition (PVD)	In test	Gun barrel IDs, small components	Cost < 0.001” thickness
Plasma spray	In test	IDs > 3” (> 1.5” with new gun). Specified for various repairs and build up in GTEs and airframes	ID > 1.5” > 0.001” thickness
[(a)] At time of reporting (2003) *(Legg, 2003b)*			

HCAT identified Thermal Spray (HVOF) as an alternative of choice for chromium. It is qualified, with limitations, for applications such as landing gear, hydraulics, and flap tracks. Research conducted on landing gear involved Boeing, BF Goodrich/Menasco, Heroux Devtek and Messier-Dowty and turbine engines involved the Propulsion Environmental Working Group (PEWG). Members of PEWG include Pratt and Whitney, GE Aircraft Engines, and Rolls Royce-Allison. The project found HVOF coatings with tungsten carbides to be equal in performance to hard chrome. Some commercial users had adopted the technology within landing gear and other aerospace systems with the caveat of certain limitations.

HCAT were sponsored by ESTCP, JG-PP and PEWG. JG-PP are the Joint Group on Pollution Prevention, created in 1994 by the US department of Defence (DoD). In 2007, NASA took over as chair for JG-PP until 2009. In 2010, the JG-PP ceased operations (Meinhold et al., 2017). PEWG was reported to be a part of the Oklahoma City Air Logistics Complex within the U.S. DoD (O’Brien, 2011). No further results for PEWG were found after 2011, it is possible that the group has ceased its activities.

- **Amcoat:** CTAC AoA 0032-02 lists the “Amcoat” project which ran in the early 2000s with an initial projected timescale of more than two years. The group comprised of nine companies, including electroplaters and components producers based in the UK, Denmark, Germany, and The Netherlands. Member organisations included the University of Nottingham and The Netherlands Organisation for Applied Scientific Research (TNO). The aim of the project was to develop an electrodeposited amorphous coating with equivalent properties to hard chrome plating; hardness, wear and corrosion resistance. Within the two-year project timeframe, no alternative for use within the general engineering sector was found. No further information is available within the AoA on the specific alternatives tested or the companies involved. No further information was found via non-exhaustive desk-based research.

- **Aerospace Chrome Elimination:** The Aerospace Chrome Elimination Team (ACE) were established in 1988, with members including Boeing, Lockheed Martin, Northrop, Grumman, NASA, UTC, Pratt & Whitney, Sikorsky, Raytheon, NAVAIR, AMCOM G4[21], ARL[22] and AFRL[23] (Lamb, 2014). A number of uses were investigated, including chrome plating. The alternative HVOF thermal spray with WC-Co or WC-Co-Cr, was the most promising in terms of performance. However, this process utilises a line-of-sight spray technique so is not suitable for more complex geometries. The outcome of studies from within the group is restricted to the members only, and is not available in the public domain.

- **Noblis[24] Cadmium and Hexavalent Chromium Alternatives 5-Year Strategy and Roadmap:** Noblis is a not-for-profit independent organisation based in Virginia, US. In May 2016, it published the review "Cadmium and Hexavalent Chromium Alternatives 5-Year Strategy and Roadmap" summarising the current status of research and implementation of Cr(VI) alternatives, primarily in US DoD applications. The review was commissioned by the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) supporting the US Department of Defence (DoD), Environmental Protection Agency (EPA) and Department of Energy (DoE). The alternatives investigated for the use hard chrome plating were:

    - Nanocrystalline Cobalt-Phosphorous
    - Cr(III) FARADAYIC
    - Cold spray
    - Electrospark deposition

  To clarify, this report provides a review of the consumption of Cr(VI) within the US DoD's use of hard chrome plating, coupled with a summary of programmes, active, retired or completed, that various organisations have participated in over the course of developing suitable, technically, and economically feasible, alternatives. **Table 3-7** summarises the projects in which members of the ADCR were included.

Table 3-7: Noblis report Alternative Technology Related Efforts in support of the US DoD for hard chrome plating: ADCR Members

Project	Alternative	ADCR Member participant
Surface Finishing of Tungsten Carbide Cobalt Coatings Applied by HVOF for Chrome Replacement Applications	HVOF	Boeing
Surface Treatment Implementation – F-35 LG HVOF	HVOF	Goodrich Corporation (United Technologies)
Surface Treatment Implementation – Sikorsky H60 HVOF	HVOF	Sikorsky (United Technologies)
Source: *https://noblis.org*		

Nanocrystalline Cobalt-Phosphorous (nCoP) is commercially available and fully compatible with hard chrome plating infrastructure. However, nCoP has higher throughput, reduced spatial requirements and reduced energy consumption. This alternative was developed by

21 U.S. Army Aviation and Missile Command
22 U.S. Army Research Lab
23 U.S. Air Force Research Lab
24 https://noblis.org/

SERDP and ESTCP. Collaboration between ESTCP and the US Navy's Environmental Sustainability Development to Integration program aims to fully qualify CoP on NAVAIR and NAVSEA (shipboard machinery components and ground support equipment).

WP-200936 (2009 to 2014) "Electrodeposited Nanocrystalline Co-P Alloy Coatings as a Hard Chrome Alternative" was sponsored by ESTCP (Prado et al., 2015, 2017), as a collaboration between Naval Air Systems Command, Integran Technologies, Inc., and Rowan Technology Group. Stakeholders (Pratt & Whitney Canada, Heroux-Devtek, Messier-Bugatti-Dowty, Boeing and DoD maintenance depots) devised protocols to test nCoP for use in landing gear, arresting gear, hydraulic cylinders, actuators and dimensional restoration of damaged components. Materials tested included:

- Aerospace steel (4130, 4340, Hy-tuff, 15-5PH, IN718, Aermet100);
- Generic steel (Low and Medium Carbon Steel);
- Copper alloys (Copper Beryllium, Aluminium Nickel Bronze, 70-30 Copper Nickel); and
- Aluminium alloys (AA7075-T6).

The alternative showed excellent performance in Dem/Val field testing and met corrosion and sliding wear test requirements. Cost benefit analysis found a payback period of 4.7 years, however further research is required prior to implementation. Masking materials that can handle high temperatures need to be identified, Taber wear performance needs to be improved and fatigue performance requires further testing.

Cr(III) is still in development, however FARADAYIC® is seen as a promising alternative. FARADAYIC® is an electrochemical technique, using a trivalent chrome plating bath rather than a hexavalent chrome bath (Faraday Technology Inc, n.d.). This is currently being tested under the Toxic Metals Reduction Program with Corpus Christi Army Depot, implementation was expected in 2019 (Lieb, 2014). The Toxic Metals Reduction Program is the Environmental Technology Acquisition Program (ETAP (The U.S. Army Research, Development and Engineering Command (RDECOM)) supporting the goals of SERDP and ECSTP to reduce the use of chromates (Hangeland, 2016).

A significant potential barrier to implementation is the requirement for collaboration between all stakeholders. The Noblis report states that US Services all have processes to ensure this collaboration occurs. Examples include the US Army Aviation and Missile Command initiating Technology Transfer Agreements to be signed by all involved parties.

Another barrier is the lack of funding. Purchase and installation of equipment to implement the process requires capital expenditure, which may not be accounted for within the overall development budget. The report states that typically budget planning needs to be done at least two years in advance.

Qualification testing is another added cost, certain processes require additional qualification depending on the application. Within the US DoD, the cost is borne by the Program Office, that may not have budgeted or planned for the additional testing. The Program Office, alongside the OEM, are then required to update the documentation to specify the use of the new technology. This is another exercise that must be budgeted for, again at least two years in advance.

Technical considerations are other potential barriers to implementation. Once a new technology has been identified, weapon systems potentially specific for the technology must be identified in order for testing to be conducted. Alternatives may have already been implemented that would be appropriate for other systems, however, as these systems have not yet been identified the testing has not been done. Other instances involve the alternative meeting the requirements of the application, however, not outperforming the Cr(VI) technology. This is an example of potential regression in performance versus the incumbent technology.

Some alternatives require significant changes in infrastructure, requiring additional space, facility modifications or additional utility requirements (such as segregation of waste streams). Implementing these changes can impact current production. The Noblis report states that collaboration is required to ensure that these barriers can be overcome

- **BluCr®:** an ADCR member reported a Cr(III) hard chrome plating process known as BluCr®. The plating bath uses Cr(III) salt, complexing agent, buffer, and additives. The process requires a nickel underlayer to be comparable to Cr(VI). As nickel is another substance of concern, substitution to this alternative requires caution. The process is also more complicated and more expensive than current Cr(VI) processes. Nonetheless, BluCr® is reported as the first functional trivalent chrome plating system on the market (Atotech, 2022).

- **Project NAPOLET:** Replacement of surface anticorrosive materials used in aerospace with more environmentally friendly technologies, reference number FW01010017. This project is within the TREND Programme. Chrome plating of steel is captured within the sub-project reference WP2 investigating the use of PVD technology and high-speed sprays based on electric arc melting, or gas or liquid burning.

- **TREND programme:** the TREND programme supports industrial research and development projects financed from the state budget by the Technology Agency of the Czech Republic and Ministry of Industry and Trade under "CzechInvest". Projects encompass advanced production technologies (security, connectivity) (*TREND Programme – Research and Development in the Czech Republic, n.d.).*

- **NCMS Validation of Functional Trivalent Chrome Plating Process:** The National Center for Manufacturing Sciences completed Phase I of a program focussed on the drop-in replacement of functional hexavalent chrome plating with a trivalent chromium plating process. Feasibility was demonstrated, leading to a phase II program which concluded in 2014, in which the process passed several key tests including hardness, thickness, plating rate, adhesion and hydrogen embrittlement[25]

- **CRONOS 2024:** Institute for Technological Research Materials, Metallurgy and Processes (IRT M2P) programme which includes 17 industrial partners and 2 academic institutions, and has the objective of evaluating the ability of Cr(III) technology to fulfil specific requirements for applications within the A&D industry.

[25] NCMS Validation of Functional Trivalent Chrome Plating Process – Phase II. Available at: Validation of Functional Trivalent Chrome Plating Process - Phase II - National Center for Manufacturing Sciences (ncms.org)

3.4.2 Consultations with customers and suppliers of alternatives

Details on consultation activities associated with the development of this AoA/SEA are provided in section 2.4.

3.4.3 Data searches

3.4.3.1 High level patent review

A patent search was performed with the aim of identifying examples of potential technologies related to electroplating/hard chrome plating. The search was performed using Espacenet[26], the European Patent Office (EPO) open access search portal. Espacenet contains over 120 million patent documents held by patent offices around the world, including North America and Asia (EPO, 2020).

In total eight independent searches were carried out stemming from the two search terms 'hexavalent chrome free electroplating' and 'electroplating without chromates'. These search terms were adapted to improve the relevance of the results and to address alternative phrasing (i.e., hard chrome plating instead of electroplating). To further refine the results, filters within the interface of Espacenet were applied. Results were first filtered by date between 01/01/2000 – 31/12/2020 to narrow the scope to more recent and contemporary technological advances. Following this, results were filtered by both International and Co-operative Patent Classifications (IPC/CPC). The IPC/CPC groups chosen were C25D3, C25D5, C25D7, C25D17 and C25D21 which were found in preliminary searches to relate specifically to "processes for the electrolytic or electrophoretic production of coatings; electroforming; apparatus therefor".

The above searches resulted in 83 patents being identified as relevant to the electroplating process. These results were cross referenced for duplicates arising from the same patent being identified in multiple searches. Cross referencing reduced the number of patents to 30. Following this the patent abstracts were screened for relevance to ensure applicability to the ADCR consortium uses, which in turn reduced the number to 21. The results are summarised below in **Table 3-8**. The following sections of this report highlight the key areas addressed by these patents and provides a brief overview of the alternatives suggested.

As with all patents, they introduce concepts and developments that may be advantageous within a given field in the fulness of time. However, it should be remembered that patents are granted for their novelty. Novelty does not necessarily translate to feasibility or applicability. Patented technologies are still bound to the requirements of the substitution process which will determine if a novel concept can be transformed into a feasible test candidate. Patents can also introduce limitations on the availability of a particular technology for example through the requirements for licencing. Where this is the case, a third party may obtain access to the technology if a licensing or some other commercial arrangement is available and meets the requirements of both parties.

Table 3-8: Patent search technology summary

Title	Patent publication reference	Technology
A method for passive metal activation and uses thereof	CN109524617A	Chromium (II) oxide, chromium (III) oxide and chromium (IV)oxide with fluoroanion composition

[26] Espacenet Patent Office (2022): Available at Espacenet – patent search

Table 3-8: Patent search technology summary		
Title	**Patent publication reference**	**Technology**
Compositionally modulated zinc-manganese multi-layered coatings	US2019264344A1	Trivalent chrome
Crystalline chromium alloy deposit	KR101557481B1	Trivalent chrome
Crystal chrome tank	BRPI0710028A2	Trivalent chrome
Electrolyte for electroplating	US10662540B2	Trivalent chrome
Method to create thin functional coatings on light alloys	TW201819692A	Hybrid coating on nickel and zinc
Integrated fluid jet system for pickling, preparation and coating of a part	ES2572151T3	High speed cold fluid stream spraying
Anti-corrosive protection layer with improved properties	ES2357260T3	Zinc-chromium mixture with organic resin (non-Cr(VI))
Chromium plating	WO2005095667A1	Trivalent chrome via physical vapour deposition
Coloured trivalent chromate corrosion-resistant enhancer agent for zinc-nickel plating and surface treatment of zinc-nickel plating layer using the same	KR102077555B1	Trivalent chrome on zinc-nickel plating
Surface pre-treatment method for pre-coated heat-treatable, precipitation-hardenable stainless steel ferrous-alloy components and components coated thereby	US2005118337A1	Zinc-nickel or cadmium plating
Multilayer, corrosion-resistant finish and method	CA2614900A1	Non-electrolytic phosphate crystals and Xylan/Teflon fluorocarbon sealer on zinc-iron
Nickel comprising layer array and a method for its manufacturing	WO2019215287A1	Nickel coating with hexa- or trivalent chrome
Nickel-plated steel sheet and method for producing nickel-plated steel sheet	EP2993257A1	Nickel-plated steel using substances such as Ti, P or Zr
Substrate with a corrosion resistant coating and method of production thereof	US10011913B2	Nickel-tin alloy using hexavalent chrome, but possibility to use trivalent chrome
Electroplated lubricant-hard-ductile nanocomposite coatings and their applications	WO2012145750A2	Nanoparticle colloidal solution
Metallic coating and a method for producing the same	WO2017005985A1	Nanodiamonds
Biocidal metallic layers comprising cobalt	US2013052482A1	Grained and/or amorphous cobalt
Electroplating solution, preparation method thereof and application of electroplating solution in electroplated metal alloy	CN104499015A	Titanium alloy plating with chrome layer
Titanium electroplating solution and plating method	WO2014010914A1	Titanium plating

Table 3-8: Patent search technology summary		
Title	**Patent publication reference**	**Technology**
Surface coatings	WO2009130450A1	Tungsten combined with amorphous Fe, Co, or Ni co-deposition
Source EPO 2020		

3.4.3.2 High level literature review

A representative, non-exhaustive technical literature review of scientific journal articles was carried out using Science Direct [27], a leading source for scientific articles covering a range of physical sciences and engineering publications, and Dimensions[28], a database containing 1.4 billion research articles. The purpose of this search was to identify any alternatives to electroplating that have been investigated in the academic field and was intended to augment the patent search and review of past AfAs. The search strategy and its evolution are summarised in **Table 3-9** and **Table 3-10** below.

Table 3-9: Search strategy electroplating in Science Direct					
Search terms in field "Title, abstract or keyword"	**Years applied**	**Hits**	**Review articles**	**Open access**	**Open access review articles**
Electroplating	-	47,136	2,024	1,702	163
Electroplating	2000-2021	32,624	1,821	1,603	163
Electroplating	2014-2021	16,004	1,268	1,226	148
Electroplating chromate free	2000-2021	1,837	1680	58	15
Electroplating chromate free	2014-2021	842	108	53	17
Electroplating chromate alternative	2014-2021	520	101	38	11
Electroplating (non-chromate OR chromate free) defence	2014-2021	92	25	11	6
Electroplating non-chromate aerospace	2014-2021	73	14	4	3
Hard chrome plating	-	3,652	149	95	13
Hard chrome plating	2000-2014	2,100	111	76	13
Hard chrome plating	2014-2021	712	70	54	13
Hard chrome plating chromate alternative	2014-2021	72	16	2	2
Hard chrome plating non-chromate aerospace	2014-2021	26	7	3	3
Hard chrome plating (non-chromate OR chromate free) defence	2014-2021	19	3	1	1
Notes: *Underlines numbers represent those articles that were analysed in detail* *"Open access" documents are ones with unrestricted access, that are available in full without payment of a licence fee*					

[27] https://www.sciencedirect.com/
[28] www.dimensions.ai

Table 3-10: Search strategy for electroplating in Dimensions			
Search terms in field "Title, abstract or keyword"	Years applied	Hits	Open access
Electroplating	-	159,010	22,002
Electroplating	2014-2021	157,010	12,754
Electroplating chromate free	2014-2021	4,957	4,287
Electroplating non-chromate aerospace	2014-2021	723	644
Electroplating (non-chromate OR chromate free) defence	2014-2021	627	60
Electroplating chromate alternative	2014-2021	6,241	611
Hard chromate plating	-	3,823	475
Hard chromate plating	-	35,002	1,438
Hard chromate plating chromate alternative	2014-2021	962	54
Hard chromate plating non-chromate aerospace	2014-2021	422	20
Hard chromate plating (non-chromate OR chromate free) defence	2014-2021	1,725	109
Notes: *Underlined numbers represent those articles that were analysed in detail* *"Open access" documents are ones with unrestricted access, that are available in full without payment of a licence fee*			

The above searches resulted in 219 papers being identified as having potential relevance to the electroplating process. The results were cross referenced for duplicates arising from the same papers being identified in multiple searches. Cross referencing reduced the number of papers to 42. Following this, the abstracts were screened for relevance to the aerospace and defence sectors, which in turn reduced the number to six. The following sections of this report highlight the key areas addressed throughout the literature and provide a brief overview of the alternative suggested.

Electroless nickel plating: Nickel-Phosphorus: Nickel-phosphorus has been investigated as an environmentally friendly alternative to hard chromium plating with comparable wear resistance. Treatment of a martensitic stainless-steel SAE HNV3 substrate under varying temperatures (320°C, 400°C, and 500°C) with the application of an unlubricated Al_2O_3 "ball-on-a-plate" showed strong wear resistance and better performance in comparison to hard-chromium coating (Goettems and Ferreira, 2017).

Electroless nickel plating: Nickel-Boron: A study conducted by Vijayanand and Elansezhian, 2014 investigated the effects of different pre-treatments and heat treatment on wear properties of electroless Ni-B coatings. Application to a 7075-T6 aluminium alloy substrate showed improvement to wear resistance after heat treatment of 400°C. Hypophosphite layer was the most effective pre-treatment and improved wear resistance for a 0.25 kg load of hardened steel over a 900 second period.

High velocity oxygen fuel thermal spray (HVOF): HVOF, a process in which mixed powder is propelled onto a substrate at a high velocity, was investigated by Vieira, Voorwald and Cioffi, 2015. A coating of Ni-Cr-B-Si-Fe applied to AISI 4340 steel was used to assess axial fatigue strength. The results indicated lower stress levels in comparison to chromium electroplated coatings (Vieira, Voorwald and Cioffi, 2015). In this method the blend of HVOF included 14.5% Cr, 4.5% Fe, 4.5% Si, 3.2% B, and Ni to balance with an application temperature of 170°C. However, reduction of axial fatigue strength may in part be due to a high porosity surface and oxide inclusion.

HVOF: An investigation reported by Hutsaylyuk et al., 2020 into the use of HVOF using two systems of ferrochrome vanadium carbides (FeCr-VC and FeCr – VC – Co) on an aluminium alloy 7075 substrate demonstrated high wear resistance. The HVOF application temperature was between 2050°C – 2300°C. A fixed friction system was used to determine abrasion by quartz sand. The results indicated that wear resistance increased with VC inclusion and further increased with the addition of cobalt.

Trivalent chromium coating: A study by Khani and Brennecke, 2019 focused on the use of an electrolytic solvent consisting of 1-butyl-3-methylimidazolium chloride ([Bmim] [Cl]), hexadecyltrimethylammonium bromide (CTAB), poly(diallyldimethylammonium) chloride (PDDA), aluminium oxide (Al_3O_3), and water for applying a chrome coating to 4130 high strength stainless steel using Cr(III). Results showed that electroplating from Cr(III) within aqueous [Bmim] [Cl] yielded a poor thickness layer. However, the addition of CTAB, PPDA, and Al_3O_3 particles improved layer thickness and hardness to a level comparable with coatings from Cr(VI) baths. Despite this, bath reusability was noted to be inadequate due to contamination produced by the anodic reactions of the platinum counter electrodes.

Double glow plasma surface alloy: A review by Yuan et al., 2020 indicates emerging modification technologies such as double glow plasma surface alloys (DGPSA) have attracted attention within the aerospace and chemical industry. Application of a low-temperature plasma which is generated by a glow discharge will energise material containing alloy elements (W, Mo, Zr, Cu, Al, Ni) causing them to evaporate and deposit on a matrix forming a surface modified layer. This modification layer will enhance the matrix material to resist external damage.

3.4.4 Shortlist of alternatives

Potential test candidates for the substitution of Cr(VI) in electroplating/hard chrome plating are shown below. This list comprises all the alternatives that were reported in the parent AfAs. These test candidates have been the focus of research and progression by the ADCR members, based on an assessment of technical feasibility and potential to be suitable alternatives to Cr(VI):

- Electroless Nickel plating;
- Nickel/nickel alloy electroplating;
- Case hardening;
    - Carburising
    - Carbonitriding
    - Cyaniding
    - Nitriding
    - Boronising
- Chemical vapour deposition (CVD);
- Nanocrystalline Cobalt-Phosphorous alloy coating;
- High velocity thermal process (including high velocity oxy fuel (HVOF) and detonation gun (D-gun) processes);
- Chromium (III) plating;

- Physical vapour deposition (PVD);
- Plasma spraying;
- General laser and weld coating technology;
- Stainless steel and high-speed steel; and
- Thermal spray coatings.

These are discussed in more detail in Section 3.5.

3.4.5 Performance requirements and testing

As described above, the Implementing Decision lists the relevant functionalities for chrome electroplating as:

- Wear resistance;
- Hardness;
- Layer thickness;
- Corrosion resistance;
- Coefficient of friction; and
- Effect on surface morphology.

In support of the initial screening, critical-to-quality tests are conducted to assess performance of proposed candidates in the laboratory environment for each of the above functionalities. Focusing on the overriding need to maintain performance requirements critical to airworthiness, safety, and reliability, proposed candidates must demonstrate performance as good as, or better than, the incumbent Cr(VI) surface treatment. If performance requirements do not meet or exceed initial generic quality control screening thresholds, the proposed candidate will not advance to test candidate status where it is subject to bespoke Breadboard[29] level testing.

Note that it is a minimum requirement to pass initial screening tests within the laboratory environment. Design owners often apply more stringent internal performance requirements as discussed in Section 3.2.1. In addition, achieving pass thresholds at the laboratory scale does not mean that the component or design will perform as intended in its operating environment. More advanced, often bespoke, testing is required to assess the viability of a test candidate against the technical feasibility criteria. Testing regimes that serve to replicate environmental in-service operating conditions are developed over decades of experience using Cr(VI). This knowledge has aided the development of test methodology aimed at laboratory scale test panels at one end of the spectrum to multi-climate chambers for simulated environment testing capable of housing airframe sections or complete working engines at the other. However, even these elaborate testing facilities cannot always replicate nature. There can still be differences between what is observed in the laboratory environment and what is experienced in the field, especially over the longer term of the operational life of the component/complete assembly. Although rigorous, exacting, and designed to give the best and most realistic information possible, there remains the chance that these complex and detailed test regimes will not fully replicate all exposure scenarios encountered at the operational level.

An additional factor to consider is that service life of equipment can be extended by ten or more years beyond its designed service life. This, together with the potential for laboratory testing to not

[29] Breadboard: integrated components, typically configured for laboratory use, that provide a representation of a system/subsystem. Used to determine concept feasibility and to develop technical data

replicate all potential operational environments, emphasises the need for the test candidates' performance to be at least as good as Cr(VI).

3.4.6 Suitability of alternatives

When assessing the suitability of an alternative reference is made to the European Commission note dated 27 May 2020 which clearly defines the criteria by which an alternative may be judged as suitable[30] In order to be considered as suitable in the European Union (EU) the alternative should demonstrate the following:

- Risk reduction: the alternative should be safer;
- The alternative should not be theoretical or only available in the laboratory or conditions that are of an exceptional nature;
- Technically and economically feasible in the EU;
- Available in sufficient quantities, for substances, or feasible as an alternative technology, and in light of the "*legal*" and factual requirements of placing them on the market; and
- Feasibility for the applicant: Are alternatives established during the authorisation procedure technically and economically feasible for the applicant?

To be available, a test candidate should meet the regulatory requirements of placing it on the market. Until the technical feasibility criteria and associated performance requirements of the use and wider treatment system are fulfilled, including all certification obligations as stipulated in the Airworthiness Directives[31], the test candidate cannot be deemed 'available'.

All civil aircraft operating in the EU are subject to Airworthiness Directives issued by EASA on behalf of the EU and its Member States, and European third countries participating in the activities of EASA. Changes to design of a product are subject to certification (EU, 2018), and can only be made following approval from the Regulator and compliance with the requirements of the appropriate Airworthiness Regulation, such as (EU) 2018/1139[32]. To reinforce this point, a civil aircraft's Certificate of Airworthiness is not valid until the Type Certificate has been approved by the Regulator (EASA, 2012)

Defence equipment is subject to standalone change protocols including approval by the relevant Member State Ministries of Defence. Therefore, a test candidate not deemed available from a regulatory standpoint would not meet all required criteria within the above definition of 'suitable'.

[30] EC (2020): Available at https://echa.europa.eu/documents/10162/13637/ec_note_suitable_alternative_in_general.pdf/5d0f551b-92b5-3157-8fdf-f2507cf071c1 accessed 25 August 2022

[31] EASA (2022), available at Airworthiness Directives - Safety Publications | EASA (europa.eu) accessed 18 October 2022

[32] REGULATION (EU) 2018/ 1139 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 4 July 2018 - on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/ 30/ EU and 2014/ 53/ EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 (europa.eu)

3.5 Assessment of shortlisted alternatives

3.5.1 Electroless Nickel Plating

3.5.1.1 Introduction

Electroless plating is a process in which metal ions in a dilute aqueous solution are deposited on a substrate by means of a heat induced reduction without the use of an electric current. Heat induced reduction is a chemical reaction in which the substrate acts as a catalyst after being heated, causing ions to continuously deposit onto the substrate. Chemicals such as hypophosphite reduce metallic ions in the electroless plating solution to form a coating. Once a metal is reduced and deposited, the metal surface acts as a catalyst for further deposition in that location (NDCEE, 1995).

The most widely used base material for electroless plating is nickel, whereby deposits usually consist of nickel-phosphorous (Ni-P). Typical bath solutions contain reducing agents such as hypophosphite to deposit Ni-P alloys. The chemical reaction for a hypophosphite bath, which is commonly used to deposit Ni-P, is shown below:

$$(H_2PO_2)^- + H_2O \rightarrow H^+ + (HPO_3)^{2-} + 2H_{ads}$$

$$Ni^{2+} + 2H_{ads} \rightarrow Ni + 2H^+$$

$$(H_2PO_2)^- + H_{ads} \rightarrow H_2O + OH^- + P$$

$$(H_2PO_2)^- + H_2O \rightarrow H^+ + (HPO_3)^{2-} + H_2$$

Another possibility to improve the layer properties is to incorporate additive particles (such as silicon carbide, diamond, PTFE (polytetratfluoroethylene), tungsten carbide) into the nickel layer to form composite coatings. By controlling the concentration of both phosphorous and additives, various coating properties i.e., lubricity and hardness can be influenced and modified selectively. The downside is added complexity affecting the uniform composition.

The bath temperature of phosphorous based chemistry is approximately 90°C. During initial testing a maximum coating rate of 10 µm/h was determined for electroless Ni-P with high phosphorous content which is about 50 % slower than functional chrome plating[33].

3.5.1.2 Status reported in original applications

Nickel is known to be one of the most common metallic elements utilised for electroless plating, to form deposits of Ni-P or nickel-boron (Ni-B) alloys. However, it was reported that it cannot be applied as a replacement to metallic chrome plating. Technical deficits to hardness, wear resistance, and layer thickness are just some attributes that make electroless nickel plating unacceptable for the aerospace industry (CTAC Consortium, 2015).

It was reported that hardness and wear resistance decrease with increased phosphorous content. Heat treatment can be applied to improve hardness; however, this may cause further issues if the treatment damages the ability of the coating to act as a barrier, by reducing corrosion resistance. Reduced phosphate concentration does not improve wear resistance enough to act as a replacement

[33] Legg, K (2003b): Chromium Replacements for Internals and Small Parts, final report

for chromium coatings. Boron-based nickel alloys have also been investigated but were discounted due to inferior performance compared to phosphate-based alloys (CTAC Consortium, 2015).

Hydrogen embrittlement was reported to be a concern on high strength steel components, as hydrogen can be evolved during the deposition process. Hydrogen is allowed to escape through microcracks in metallic chrome coatings, whereas a less porous layer is formed with electroless nickel. Therefore, some surface area must be left unplated for applications where hydrogen needs to escape during the de-gassing heat treatment process.

The minimum requirements for metallic chrome coatings for hardness are 700-900 HV for a like-for-like hard chrome plating alternative. As deposited, electroless nickel layers do not fulfil this requirement, but for non-heat treated electroless nickel, 500 HV can be acceptable for exceptional applications. The specified minimum hardness for nickel-phosphorous qualification was reported to range from 450 HV (without hardening) to 750 HV (with hardening). It is worth noting that corrosion resistance decreases through the hardening process. Heat treatment at temperatures above 400°C for the purpose of enhancing hardness is not always considered suitable due to the degradation and distortion of heat sensitive materials widely used in aerospace and defence applications. Hardness can be achieved in some, but not all, applications.

For electroless nickel coatings in an as-deposited state (with no hardening), the corrosion performance was reported to be sufficient, although performance among technologies can vary. It was found that the nickel alloy with the highest phosphorous content was the only coating that could match the metallic chrome coating performance, however the hardness requirements could not be met by this coating, with a hardness of around 530 HV. For applications where corrosion resistance is critical, unhardened Ni-P is preferred.

Electroless nickel layers were reported to achieve a maximum thickness of 100µm, which is the minimum quality control requirement for aerospace and defence applications. It was reported that as a consequence this requirement could not be met satisfactorily.

One of the main issues reported during the assessment of Ni-P plating can be the lower reliability of the electroless plating process compared to the conventional Cr(VI) method. Process conditions are difficult to maintain, and there is a high sensitivity to fluctuations in the process that can affect layer quality and adhesion properties.

It was concluded that the scope of application for electroless nickel coatings in the aerospace industry was restricted to specific niche applications. Acceptable hardness and corrosion resistance could not be obtained at the same time according to requirements of the sector, and therefore electroless nickel-phosphorous plating was determined not be a fully suitable alternative to electroplating with Cr(VI).

3.5.1.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level or Electroless Nickel Plating

It has been reported by one company that electroless nickel plating offers potential for a suitable solution on various components, and it is currently in use in their operations. However, the inability of the coating to provide adequate layer thickness limits its usefulness in some cases.

It has been reported that, for application of electroless nickel plating on gun barrels, the melting point of the nickel-phosphorous alloy is too low (1,000°C) to be able to withstand the extreme high temperatures generated during firing. Moreover, the coating has been found to have insufficient chemical resistance against the nitrogen oxides formed during firing. It has also been reported that the adhesion of the coating to the substrate is insufficient due to the low elasticity of the deposited coating.

It has been noted by one member that some components would not be able to accept nickel-phosphorous plating as an alternative to electroplating, where the solution would be to have the Design Office create a brand-new design. However, another member reports that nickel-phosphorous plating can be acceptable for some components when combined with a thermal post treatment.

Economic feasibility of Electroless Nickel Plating

The parent AfA concluded that, based on qualitative information, the per-component cost of electroless nickel plating should be considered similar to the cost of hard chrome plating. Although no quantitative assessment has since been undertaken, members reported that the cost of electroless nickel plating is likely to be significantly higher due to the higher operating temperatures and requirement for specialty formulations rather than commodity solutions to be used. In the case of electroless nickel plating, the solution must be regularly analysed and replenished/replaced with much greater frequency than a chrome plating solution.

Health and Safety considerations related to the use of Electroless Nickel Plating

Hazardous divalent nickel (Ni(II)) salts such as nickel sulphate (CAS No. 7786-81-4) and nickel dichloride (CAS No. 7718-54-9) are used in the nickel plating bath to deposit the nickel undercoat. These substances are classified as carcinogenic (Cat. 1A), toxic for reproduction (Cat. 1B), and mutagenic (Cat. 2) according to the harmonised classifications listed in Annex VI of the CLP Regulation. Additional health hazards include skin and respiratory sensitisers (Cat. 1). Due to the hazardous properties of the nickel salts, the risks relating to this alternative must be carefully evaluated to avoid the possibility of regrettable substitution.

Availability of Electroless Nickel Plating

Electroless nickel plating is a well-established, commercially recognised process, with a number of companies supplying the coating solutions and equipment required for the process. This said, there is the potential more specialised equipment would need to be designed for use with components possessing complex geometries.

It has been reported by one member that qualification is in progress for electroless nickel plating, but more (potentially full-scale) tests may need to be carried out if certain components require re-design. Another has reported that electroless nickel plating is already specified and being used as surface protection in the design notes.

Suitability of Electroless Nickel Plating

Whilst the process and technology are well-defined, established within many industries, and economically viable, members report that, as with other alternatives to chrome electroplating, electroless nickel plating is not a solution across all components. For those components where the process is considered viable, it may need to be developed alongside other test candidates, such as HVOF and chemical vapour deposition with Cr_2O_3 plasma spraying.

As noted above there are also significant safety concerns caused by the introduction of an alternative carcinogenic substance to the process, with the potential for regrettable substitution.

3.5.2 Nickel/nickel alloy plating

3.5.2.1 Introduction

Comparable with functional chrome plating, nickel and nickel alloy electroplating differs in the anode design, bath chemistry, and operating parameters such as voltage. A typical bath for nickel coating contains nickel sulphate, nickel chloride and boric acid.

Contamination with metal impurities is common for nickel-plating solutions, and these must be removed by low current density electrolysis on a corrugated cathode.

3.5.2.2 Status reported in original applications

It was reported that when combined with alternate layers of metallic chrome coating its performance was adequate for key functionalities such as hardness, friction, wear, corrosion, and adhesion. However, it was reported that the application of a single nickel electroplated layer alone exhibited greatly reduced performance with regard to the above functionality, rendering it ineffective as a replacement to chrome plating (CTAC Consortium, 2015).

It was reported that heat-treatment was required to ensure an acceptable degree of hardness. This heat-treatment inevitably leads to damage of the coating and in turn may compromise its corrosion barrier properties (CTAC Consortium, 2015).

Nickel and nickel alloy electroplating is usually applied as an undercoat prior to hard chrome plating to provide sufficient corrosion protection. One of the key parameters that must be fulfilled by a functional chrome plating alternative is the hardness performance. For the majority of electroplated nickel layers, a hardness value of < 400 HV was achieved. Hardness can be increased by high temperature annealing, but this simultaneously reduces corrosion resistance by a significant amount. Heat sensitive structure alloys cannot be subject to post-treatment with heat. Where heat treatment is possible, it is commonly used for stress relief purposes and for the evolution of hydrogen in order to minimise brittleness – usually at temperatures between 140-190°C with a maximum of 250°C. Electroplated nickel layers that have not undergone post heat-treatment do not reach the minimum threshold for hardness required in the aerospace sector, with 450 HV reported without hardening, to 750 HV with hardening (with decreased corrosion resistance).

Due to the extensive use of heat sensitive substrate materials in aerospace and defence applications, required hydrogen evolution temperatures < 150-250°C and stress relief temperatures > 350°C, it is not an option to enhance hardness performance using heat treatment. As the nickel layer is compact and does not contain the same microcracks as metallic chrome coatings, post-treatment steps such as sealing, or lacquering are not suitable.

For coefficient of friction, the minimum requirement for lubricated metallic chrome coatings is < 0.2. It was reported that coefficient values for electroplated nickel layers were higher, therefore they are not able to fulfil this requirement.

Compared to metallic chrome coatings, the wear resistance of electroplated nickel layers was reported to be significantly lower, and therefore not sufficient for it be a suitable replacement.

In conclusion, it was determined that nickel and nickel alloy electroplating was not considered to be a suitable alternative to the conventional Cr(VI) electroplating due to insufficient performance on hardness, friction and wear resistance.

3.5.2.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Nickel/Nickel Alloy Plating

It is noted by one member that nickel/nickel alloy plating does not address the full scope of electroplating with Cr(VI) substances, but could have potential for anti-fretting applications. However, that alone would not be suitable for wear resistant coatings.

Economic feasibility of Nickel/Nickel Alloy Plating

The direct challenge for members investigating nickel/nickel alloy plating as an alternative to chrome electroplating is the increase in operating costs as well as the cost of a long test process for certifications. The operational costs will increase due to the following impacts:

- **Raw material costs:** in general, the price of raw materials for nickel/nickel alloy plating processes is higher than the price of Cr(VI)-based formulations (i.e., chromium trioxide) currently in use. The bath life of the alternative process is shorter; therefore, a higher quantity of the potential candidate is required per annum (and hence per unit of production); and
- **Waste disposal cost:** potential increases in the volume of waste due to shorter bath life and therefore disposal costs rather than current levels.

Another major cost factor identified in relation to nickel/nickel alloy plating as an alternative to chrome electroplating is the time to certification. The time required is affected by both the testing requirements for validation and qualification of the use of the test candidate on components, as well as the process for qualifying or accrediting suppliers against the implementation of the alternative. According to several companies, the time needed across the R&D phase is significant due to the need to undertake a range of tests with limited specialists in test facilities. This is then followed by the time required for gaining certifications due to the number of new certifications being requested, e.g., by EASA, and limits the available resources for processing and approval.

Health and Safety considerations related to the use of Nickel/Nickel Alloy Plating

Hazardous divalent nickel (Ni(II)) salts such as nickel sulphate (CAS No. 7786-81-4) and nickel dichloride (CAS No. 7718-54-9) are used in the nickel plating bath to deposit the nickel undercoat. These substances are classified as carcinogenic (Cat. 1A), toxic for reproduction (Cat. 1B), and mutagenic (Cat. 2) according to the harmonised classifications listed in Annex VI of the CLP Regulation. Additional health hazards include skin and respiratory sensitisers (Cat. 1). Due to the hazardous properties of the nickel salts, the risks relating to this alternative must be carefully evaluated to avoid potential for regrettable substitution

Availability of Nickel/Nickel Alloy Plating

As nickel electroplating is commonly used as an undercoat for functional chrome plating, it is a commercially available process. There were no examples reported by ADCR members of a qualified process using nickel electroplating as a standalone process in the A&D sector. The process is therefore not considered to be generally available.

Suitability of Nickel/Nickel Alloy Plating

Once again, the technology and bath solutions required for this process are readily commercially available, however their implementation would represent a significant increase in cost compared to the current process. The safety concerns associated with substances used in the plating bath are also significant. Further to this, the parent AfA reported that the aerospace sector does not consider nickel electroplating a suitable like-for-like replacement for chrome plating and this remains the case.

3.5.3 Case hardening

3.5.3.1 Introduction

Case hardening is a very common process used to harden the outer surface of a metal, creating a hard metal outer layer ("case") and thus protecting the deeper metallic material (CTAC Consortium, 2015). All case hardening processes involve heat treatment of a metal substrate, where an atmosphere in excess of a gaseous (or liquid) phase of a chosen substance is used to diffusively enter the other layer of the metal substrate. This creates the case. The typical process temperature for case hardening is between 500 to 1,000°C (TURI, 2006).

Case hardening is usually applied on steel, low carbon steel and other iron alloys. For different types of case hardening, the substance used to form the case differ: carburising uses carbon (from a source such as carbon monoxide), carbonitriding is based on nitrogen and carbon, cyaniding uses cyanide, nitriding uses nitrogen and boronising uses boron.

For case hardened surfaces, a hardness between 550 to 1,200 HV can be achieved depending on the process, temperature, substance, and substrate used. Corrosion performance was not improved using any of the case hardening techniques, and the corrosion resistance of the hardened materials was comparable or worse than that of the base material. This is because case hardening does not actively provide a corrosion protective barrier.

The hardness of a case hardened surface is determined by the process used as well as the substrate, and by extension its suitability for application in the aerospace industry. There were varying reports on whether the hardness requirements were reached by case hardened materials depending on the application. Some reports state that case hardening could be applicable to a limited number of steel alloys and is particularly unsuitable for structural components, such as landing gears, that have high requirements. Differing minimum requirements for hardness across different components reflect the varying suitability of case hardening techniques; for example, a hardness requirement of 400 HV may be sufficient for components with lower requirements. However, the majority of components require at least 700 HV to be met for a test candidate to replace Cr(VI)-based electroplating. Therefore, with a range from 550 to 1,200 HV for case hardened surfaces, the hardness parameter for some substrates and processes may be achieved.

In general, case hardening was not considered a suitable replacement for hard chrome plating at the time of the original Applications. Important process temperature and performance parameters could not be met, such as the corrosion resistance. Due to the majority of airplane components being constructed from temperature sensitive materials which have processing temperatures below that of the case hardening, it was not deemed an acceptable alternative.

3.5.3.2 Status reported in original applications

Case hardening was reported to only be suitable for steel substrates, specific steel alloys and materials able to withstand the high process temperature. Heat treatment on aluminium alloys cannot exceed temperatures over 150°C, and for high strength steels temperatures cannot exceed 250°C. Consequently, heat treatment of these substrate materials at temperatures between 340 and 400°C for prolonged periods of time (several hours) would not be suitable to achieve better hardness performance.

3.5.3.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Case Hardening

It has been reported by one member that case hardening is in development for a limited scope and for specific steel substrates, however there are issues to be expected with regards to corrosion resistance.

It has been reported by another member that carburising is currently used in some of their applications in combination with chromium electroplating or other surface processes (such as phosphate coatings). Based on their experience, the heat treatment involved does not provide adequate corrosion protection. This company also reported that nitriding is used, but not as an alternative to chrome electroplating.

Economic feasibility of Case Hardening

In the parent AfA it was reported that the cost factor for case hardening processes compared to functional chrome plating was three times higher, however no further quantitative analysis of economic feasibility was conducted.

No further information on economic feasibility was reported by ADCR members.

Health and Safety considerations related to the use of Case Hardening

The substances required for the case hardening process are reported below, with information on the classification of each substance according to Regulation (EC) 1272/2008 also provided:

- Sodium cyanide (CAS no. 143-33-9) – Met. Corr. 1; H290, Acute Tox. 1; H300, Acute Tox. 1; H310, Acute Tox. 1; H330, STOT RE 1; H372, Aquatic Acute 1; H400, Aquatic Chronic 1; H410
- Potassium cyanide (151-50-8) – Met. Corr. 1; H290, Acute Tox. 1; H300, Acute Tox. 1; H310, Acute Tox. 1; H330, STOT RE 1; H372, Aquatic Acute 1; H400, Aquatic Chronic 1; H410
- Carbon monoxide (630-08-0) – Flam. Gas 1; H220, Acute Tox. 3; H331, STOT RE 1; H372, Repr. 1A; H360D
- Ammonia (7664-41-7) - Flam. Gas 2; H221, Skin Corr. 1B, H314, Acute Tox. 3; H331, Aquatic Acute 1; H400
- Boron (7440-42-8) - Not classified as hazardous

Although the substances required for case hardening, replacing the non-threshold carcinogen used in electroplating with chromium trioxide, represent a less hazardous alternative, one of the substances meets the criteria for identification as a substance of very high concern (SVHC) and inclusion on Annex XIV of REACH. Substitution to this use could therefore be considered to represent a regrettable substitution.

Availability of Case Hardening

Case hardening is reported to be commercially available, but only for very specific applications in the automotive sector. There were no examples reported by ADCR members of case hardening as a qualified process in the A&D sector. The most advanced development program reported by members was at TRL 3 and is being challenged by re-design options.

Suitability of Case Hardening

Whilst fulfilling the requirements for hardness for some substrates and processes, due to corrosion resistance and non-repair issues case hardening is not expected to become a suitable replacement for functional chrome plating in any but a few niche uses in the A&D industry. For these uses, development programs are still at an early stage.

3.5.4 Chemical Vapour Deposition

3.5.4.1 Introduction

Chemical Vapour Deposition (CVD) is a process in which a reactant gas (usually in a mixture with inert gases) enters a reaction chamber at room temperature, and is then heated or passed over a heated substrate at temperatures normally above 1,000°C. Materials are introduced to the deposition area in the gas phase, which contain the desired coating material such as metal halides, metal carbonyls, hydrides, or organometallic compounds in vapour phase. Examples of coating materials include titanium carbide (TiC), titanium nitride (TiN), titanium carbon nitride, silicon carbide, titanium boride and aluminium oxide.

Following absorption onto the substrate surface, reactants are decomposed and react with the substrate to form a coating. By-products are then removed from the chamber. Carrying out the CVD process under sub-atmospheric pressure allows the reduction of unwanted gas-phase reactions and improves film uniformity across the substrate.

3.5.4.2 Status reported in original applications

CVD was discussed in the parent Applications in the context of thin CVD and thick CVD.

Thin CVD, referred to mainly as CVD, was reported to be unequal in achieving the corrosion protection as demonstrated by metallic chrome coatings. It was also reported that many CVD coatings, for example TiN and TiC, are not able to protect substrates due to their porous structure and low thickness. Therefore, these would not be suitable as alternative to Cr(VI) electroplating. The vacuum conditions required for the process limit the scope of components to be coated, for example where the component size is concerned.

Surfaces treated with CVD can achieve at least 1,500 HV, which fulfils the minimum hardness requirement in the aerospace sector. Despite reports that good results were seen for friction characteristics, CVD did not meet requirements for wear and shock resistance due to the very low thickness of CVD compared with metallic chrome coatings.

Within the aerospace sector, high strength steels and aluminium alloys are widely used materials due to their low processing temperatures. The deposition temperature for aluminium alloys must be below 150°C, and for high strength steels must be below 250°C. These materials cannot be used with CVD processes due to exposure to much higher temperatures. Additionally, the CVD process is carried out in a vacuum, whereby the size of the vacuum chamber would depend on the component size. CVD processes such as Diamond Like Carbon (DLC) is suitable for small components such as small rods or keys, but in general CVD is not suitable for large components such as landing gears.

It was concluded that, as a specialised technique, CVD would be suitable for specific niche applications, but is generally unsuitable as a replacement for hard chrome plating with Cr(VI).

Thick CVD is applied in a similar process to thin CVD and involves a reactant gas that is a source of tungsten and one that is a hydrocarbon. The processing temperature can be kept below 500°C, depending on other reaction conditions, which allows application to a wide range of materials such as steel, stainless steel, nickel, copper, cobalt, and titanium alloys. The resultant coating is graduated homogenous, non-porous and bind-free tungsten/tungsten carbide exhibiting sliding wear properties and barrier corrosion resistance. Changing the processing conditions can allow different properties such as hardness and toughness to be obtained.

Thick CVD can be adapted to a wide variety of components, shapes, and sizes in the aerospace sector. As it is not limited to line of sight, this makes it particularly suitable for components with complex geometries that require wear protection up to “high load” situations.

The typical hardness of the coating can range from 800-1,600 HV depending on the type. Coatings provided by thick CVD are usually around 50 µm thick, with the maximum layer thickness achieved in excess of 100 µm. As a consequence, it is possible to use it as a replacement to a metallic chrome coating without changing the tolerances. However, the relatively high processing temperatures means that materials changes may be required more often. Otherwise, the heating process step may have to be incorporated into the heat treatment regime of the material. At the time of reporting, typical reaction chambers could accommodate maximum dimensions up to 1.2 m. The process required nickel undercoats on all substrates to be coated, produced by electrolytic or electroless processes using nickel salts. However, there were plans to replace these with other undercoats.

The coating had shown itself to be equal or superior to metallic chrome coatings in sliding wear and bench testing in structures like bronze bearing materials but not against harder substrates. Tests showed that the coating offered good barrier corrosion protection and that it was able to coat complicated geometries. Its use in military aircraft is limited, and at the time of the original Applications, it was being qualified by a major commercial aircraft manufacturer. However, the coating was not deemed suitable for many aerospace materials due to its high process temperature, and the fact that it requires lubrication under high load. The main application of thick CVD was likely to be for complicated geometries, especially under high load, and it was hoped to be an environmental improvement over electroless nickel.

Thick CVD could not be considered as a general replacement to metallic chrome coatings due to the processing cost and high temperature requirements, however it does provide a thick coating with relatively good tribological properties which are suitable for materials with mechanical properties that are not affected by high process temperatures, such as many stainless steels. In particular, it is suitable for components with complicated geometries for which thermal spraying would be unsuitable.

3.5.4.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Chemical Vapour Deposition

It is reported by one member that DLC is a chosen solution in a small number of cases since the film capability and suitability for use on steel makes it applicable for certain piston jacks. However, it is still not suitable for the majority of piston jacks, and due to the film thickness requirements, re-design is required for each component, which adds a time and cost burden. Further consideration is required for additional components owned by this company.

Another company reports that DLC fails to comply with the process requirements for defence applications due to the high process temperature.

Economic feasibility of Chemical Vapour Deposition

The parent AfA reports that costs (including energy consumption) were higher than for functional chrome plating – particularly where the processed volumes are low.

No further information on economic feasibility was reported by ADCR members, and no quantitative assessment has been undertaken.

Health and Safety considerations related to the use of Chemical Vapour Deposition

There have been no detailed assessments reported for the use of CVD processes as an alternative to Cr(VI)-based electroplating at this stage. The coating is prepared in a closed system, so it is not expected that there is any exposure during use. The process eliminates the use of non-threshold carcinogens like chromium trioxide. It has been reported by one company that, if CVD is chosen for implementation as an alternative process, a full assessment of the hazards and risks related to its use will be carried out.

Availability of Chemical Vapour Deposition

One member reports that CVD is qualified for specific scope by some industries. To their knowledge the process is long and expensive, with a low availability in terms of the limited size of the coating chambers.

Suitability of Chemical Vapour Deposition

Whilst removing a number of the safety concerns associated with the use of chromium trioxide, chemical vapour deposition is unsuitable for use in all but a small number of niche applications in the aerospace industry, and technically not feasible for introduction by the defence industry. This, combined with the higher costs and low availability of the equipment required means this is not an alternative considered to be general suitable by the A&D industry.

3.5.5 Nanocrystalline Cobalt-Phosphorous Alloy Coating

3.5.5.1 Introduction

Nanocrystalline cobalt phosphorous alloy (nCoP) coatings are electrodeposited in an aqueous bath process using pulse plating technology. Controlled deposition of nano-grains is enabled through the pulse technology, resulting in an ultra-fine grain structure throughout the entire coating from the substrate surface (5-15 nm).

3.5.5.2 Status reported in original applications

The similarities between nCoP and the electroplating process mean that the alternative process is compatible with the hard chrome plating infrastructure. This allows for the possibility of a drop-in replacement to the conventional Cr(VI)-based method. However, at the time of the original Applications it was reported that the cobalt plating process was not a mature technology and general cobalt plating solutions were in a low TRL stage.

As mentioned, the hardness requirement for a coating in the aerospace sector must be 700-900 HV. Coatings of nCoP can achieve 600-700 HV as-deposited, therefore they do not meet the requirement. Using heat treatment to increase the hardness performance is not an option, due to the heat sensitivity of substrate materials used most commonly in the aerospace industry (e.g., aluminium alloys, high strength steel). Deposition temperature for aluminium alloys must not exceed 150°C, and for high strength steels must not exceed 250°C. So, heat treatment of these materials to 300-400°C for several hours would not be suitable to enhance hardness performance. Moreover, the hardness requirement cannot be fulfilled by as-deposited coatings, and due to material degradation, annealing is not an option for increasing hardness.

It was reported that although the nCoP met the performance criteria for corrosion resistance, it could not provide the layer thickness required for the substitution.

Due to the insufficient technical performance of nCoP coatings, they were not deemed a suitable replacement for Cr(VI)-based electroplating.

3.5.5.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Nanocrystalline Cobalt-Phosphorous Alloy Coating

One member reports that nanocrystalline cobalt phosphorous alloy coating does not address the full scope of electroplating with Cr(VI) considering its unsuitability as a wear coating.

Another member reports that, from a technical viewpoint, these types of coatings may be potentially satisfactory, however there have been no developmental advancements due to commercial and IP concerns.

Economic feasibility of Nanocrystalline Cobalt-Phosphorous Alloy Coating

The parent AfA reported that energy consumption can be reduced for nano Co-P coating, whilst throughput is increased. Despite the higher plating efficiency however, the costs of nano Co-P plating were reported to be slightly higher.

No further information on economic feasibility was reported by ADCR members, and no quantitative assessment has been undertaken.

Health and Safety considerations related to the use of Nanocrystalline Cobalt-Phosphorous Alloy Coating

The substances required for the case hardening process are reported below, with information on the classification of each substance according to Regulation (EC) 1272/2008 also provided:

- Cobalt (II) dichloride (7646-79-9) - Acute Tox. 4; H302, Skin Sens. 1; H317, Resp. Sens. 1; H334, Muta. 2; H341, Carc. 1B; H350i, Repr. 1B; H360F, Aquatic Acute 1; H400, Aquatic Chronic 1; H410.
- Orthophosphoric acid (7664-38-2) - Skin Corr. 1B; H314.

Like chromium trioxide, cobalt (II) dichloride is a non-threshold carcinogen. This alternative process therefore does not represent a reduction in hazard and has the potential to be a regrettable substitution.

Availability of Nanocrystalline Cobalt-Phosphorous Alloy Coating

In the parent AfA it was reported that Nano Co-P alloy coating is in early laboratory stages at low TRL. Whilst cobalt is theoretically a readily available substance for use in this alternative process, its primary source is the Democratic Republic of Congo (DRC), which is recognised as a conflict-affected and high-risk area (CAHRA). Availability of cobalt for use in A&D products would therefore be dependent on the volumes being available via supply chains meeting relevant due diligence standards.

Suitability of Nanocrystalline Cobalt-Phosphorous Alloy Coating

It was reported in the parent AfA that nano Co-P coatings are not technically feasible for the A&D sector, nor are they a desirable replacement from a health perspective. Based on the feedback provided by ADCR members during the consultation exercises, technical feasibility, commercial and intellectual property (IP) concerns continue to prevent this from representing a broad suitable alternative to chrome plating.

3.5.6 High Velocity Thermal Processes

3.5.6.1 Introduction

The High Pressure/High Velocity Oxygen Fuel (HP/HVOF) process is a supersonic flame spraying process based on the combustion of a fuel gas or liquid (e.g., kerosene) with oxygen under pressure (< 1MPa). The pressure in the combustion chamber is high (in the order of 9 Bar). The energy produced in the combustion chamber is used to melt the powder and accelerate it toward the gun via a convergent-divergent nozzle.

3.5.6.2 Status reported in original applications

High velocity thermal processes include HVOF and detonation gun (D-gun) and super D-gun processes. HVOF is an already qualified process used by some aerospace companies for specific components such as landing gears, hydraulics, and flap tracks, particularly with WC-Co-Cr coatings. Regarding the hardness requirements, coatings based on WC-Co are equivalent to metallic chrome coatings, however other HVOF coatings based on molybdenum and CoCrMo are softer (> 400 HV).

As HVOF is a line-of-sight process requiring gun-to-substrate distance, limiting the geometry of the component to be treated, making it unsuitable for coating complex shapes, inner surfaces and small components. Component geometry directly and strongly influences the deposition velocity, decreasing with increasing complexity. Due to these limitations, HVOF is only suitable for a specific range of larger components with simple geometry.

At the time of the original Applications, it was reported that WC- and Mo-based layers had thicknesses in the range of 100-200µm, which fulfilled the minimum requirements for the aerospace sector (i.e., around 100µm).

The majority of the coatings did not fulfil the minimum corrosion resistance requirements. However, CoCrMo, WCCoCr and Mo- layers were tested for corrosion resistance and found varying levels of success. CoCrMo-layers achieved 750 hours in neutral salt spray test. It was reported that the good corrosion resistance with CoCrMo coatings were given to substrates with an undercoat. Coatings such as CoCrMo and Mo against alloyed steel performed worse in NSST, reaching only 117 hours. Compared with 860 hours as demonstrated by metallic chrome coatings, which makes molybdenum coatings generally unsuitable for corrodible substrates.

In conclusion, HVOF is successfully used as a process in specific applications such as landing gears with WCCoCr coatings. However, it is not a like-for-like replacement for conventional Cr(VI)-based electroplating.

3.5.6.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of High Velocity Thermal Processes

One member reports that, although HVOF is qualified, it does not meet the full scope of requirements as electroplating with Cr(VI) does. Some restrictions have been observed, including the spraying methods incompatibility with the complex geometries of some components (i.e., components with small internal diameters). On aluminium and titanium alloys, the application of HVOF is limited to areas with low deformations and cannot be applied on metallic matrix composite (MMC) or magnesium alloys. Therefore, a case-by-case analysis may be necessary, with potential full-scale tests, to validate the change.

For another member, HVOF processes are the chosen solution in many cases. Again, some components have unsuitable geometry for this application, and some components require thin coatings that cannot be achieved by HVOF processes. This same company has not investigated D-gun processes on the grounds of commercial and IP concerns.

The nature of HVOF as a line-of-sight process with a spray distance of 150-300 mm is cited as a reason why one member has not pursued its development as an alternative to Cr(VI)-based electroplating. The inability to coat interior surfaces such as gun barrels, and the extreme difficulty with coating complex geometries cannot be overlooked when considering the implementation as a processing technique in the aerospace and defence sectors. Moreover, the resulting surface was reported to be typically rough and may require post-machining, which is not possible on components like gun barrels.

A further issue comes when removal of the coating is required during MRO activities. Conventionally stripping would only be possible via a grinding activity, however this could present difficulties with this test candidate due to the hardness of the coating.

Economic feasibility of High Velocity Thermal Processes

When considering the economic feasibility of HVOF, it is reported by one member that the capability for piston jacks exists already within the current supply chain, and there were no significant capital costs expected. However, the full cost implications on a unit level were not able to be estimated as quotes have not been received or requested. For other components, less is known about the implications, as work streams are at an earlier stage. However, the intention is to use off-the-shelf technology in the supply chain so there are no significant capital costs expected, although the impact on unit cost and lead times could still be significant.

It is reported that there will be an increased cost of production when moving from Cr(VI)-based electroplating to HVOF processes due to the nature of the process and the limited supply chain capability. One company indicates that more investment in new equipment is required by both the manufacturer and the supplier, as well as more investment in staff training.

In summation, the direct challenge of substitution using HVOF processes is the increase in infrastructural and operational costs. It is anticipated that there is a requirement for additional equipment by both the manufacturer and the supplier for implementation, due to the nature of the HVOF process. The operational costs will increase due to the following impacts:

- **Energy costs:** as the process is combustion-based and requires a special chamber for performing the process, there is an increase in overall energy/fuel cost for running the process; and
- **Training costs:** there is a requirement for training staff to run the process. Thus, there will be an increase in training costs.

These additional costs will be a dominant factor to be considered especially by small and medium-sized companies before switching to the potential candidate.

Health and Safety considerations related to the use of High Velocity Thermal Processes

The parent AfA reported an example of a coating material often used for high velocity processes, which was classified in accordance with Regulation (EC) 1272/2008 as: Skin Irrit. 2, Eye Irrit. 2, STOT SE 3, Carc. 2. This represents a significantly reduced hazard profile when compared to chromium trioxide.

Availability of High Velocity Thermal Processes

One member reports that a supply chain is in place for HVOF, but more (potentially full-scale) tests may need to be carried out if certain components require re-design.

Another company reports that the supply chain for HVOF as an alternative process to electroplating with Cr(VI) is in place for new development projects. However, they note that on qualified products, the plating process must be approved by the design owner/customer through modification of relevant documentation (e.g., source control drawings, CMM, technical documents). Even if alternative processes are available, the company would only be able to change the actual process if approved by the design owner or type certificate holder.

Supply chains are reported by another member to be in place since HVOF is carried out in the supply chain. A phased transition would need to be agreed with suppliers and is seen as the most likely way forward. However, another member notes that the capacity of this supply chain is not currently sufficient to meet the demand in the case of substitution for Cr(VI)-based electroplating.

As with Nanocrystalline Cobalt-Phosphorous alloy coating, this alternative is based on a cobalt coating, and the issues presented above regarding the origin of this raw material would also apply here.

Suitability of High Velocity Thermal Processes

It is noted by one member that HVOF as an alternative to chrome electroplating is not acceptable on some components, where the substitution would require the Design Office create a brand-new design.

It is also reported that HVOF cannot currently be properly applied to internal surfaces and complex geometries due to technological and process constraints, and that it is not currently feasible to use HVOF for ball screw rolling surfaces. Thickness of HVOF coatings is significantly larger when compared to hard chrome plating, which can have knock-on effects on the design of the component, and make it an unsuitable substitute for small components and those with complex geometries.

One member reports that the proposed use of HVOF for piston jacks can be implemented as a like-for-like substitution in terms of dimensions and surface finish. The coating material composition will be very different, so part numbers will need to change, adding a time and cost burden. Progression of work towards TRL 4 suggests that the proposed solution will perform as well as the current Cr(VI)-based process.

For one member where HVOF is the preferred alternative solution for plating piston jacks, they have reported that their program is relatively advanced. However, there are some aspects of the development that they have reported as taking longer to complete than initially anticipated (due in part to disruptions caused by COVID-19 and consequent supply chain issues, etc.). Progression of the modifications and part number changes required is anticipated to take a significant amount of time, which will extend beyond the deadline of the current Authorisation.

As reported, HVOF is currently used as a solution to chrome electroplating for some applications. However, as with other alternatives, it cannot be applied across all components, particularly those which are small and have complex geometries, and therefore requires development alongside other alternative treatments and methods, such as electroless nickel plating and chromium oxide plasma spraying. A case-by-case analysis is required for each component.

3.5.7 Chromium (III) Plating

3.5.7.1 Introduction

The use of chrome (III) as an alternative to chrome (VI)-based hard plating has distinct disadvantages mainly due to the additional manufacturing steps and increased heat treatment required in the plating process[34]. Moreover, the high stability of Cr(III) complexes means their reduction to metal chrome is more difficult to manage. This presents challenges in meeting the technical feasibility criteria required for the performance of the hard chrome plating.

3.5.7.2 Status reported in original applications

It was reported that trivalent chrome can be plated by electrodeposition using a bath of chromium trichloride electrolyte. In many ways, the process is similar to that of hexavalent chrome plating. However, for Cr(III) pulse plating is required alongside a different anode and electrolytic solution composition. Switching to a pulse plating method would involve more expensive equipment than currently used for hexavalent chrome but would likely not have significant impacts on overall process cost. Trivalent chromium can be plated at lower temperatures than hexavalent chrome (20-60°C as opposed to 50-60°C) but requires a narrower pH range 2.1-2.3 as opposed to 1.0-3.0) CTAC Consortium, 2015).

It was reported that chrome (III)-based alternatives meet the aerospace hardness requirements and show better wear resistance than Cr(VI) plated surfaces. However, there are several issues surrounding the presence of macrocracks in the surface. These macrocracks lead to very low corrosion resistance which is a key criterion for use in replacing hexavalent chrome-based coatings. Trivalent chrome also fails to meet the required layer thickness for the majority of the industry sectors including aerospace. It should be noted, however, that there is potential for macrocracking problems to be solved by use of alternative processing techniques.

[34] Goettems FS. & Ferreira JZ. Wear behaviour of electroless heat treated Ni-P coatings as alternative to electroplated hard chromium deposits. Mat Res (2017), 20:5.

3.5.7.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Chromium (III) Plating

As mentioned above, Cr(III) complexes display higher stability to Cr(VI) complexes, making their reduction to metallic chrome more difficult to manage. This effects the ability to achieve the correct layer thickness for a metallic chrome coating, which in turn makes it difficult to achieve sufficient wear and corrosion resistance. Additional heat treatment on the Cr(III) coating can make it possible to achieve these functions, although this can lead to defects in the layer. However, one member reports that initial friction investigations on Cr(III)-based alternatives show promising results even with an unstable microstructure. A full characterisation has not yet been performed, but it was shown that behaviour of the coating improved if friction contact occurs in oil media (i.e., in gearbox applications).

The hardness of a metallic coating evolved from a Cr(III)-based process does not differ noticeably from those obtained from Cr(VI)-based baths, however there is a difference in the structure of the coatings. Cr(VI)-based hard coatings are deposited in a hexagonal crystal, reorganising itself into a tighter body-centred cubic structure which allows the release of built-up hydrogen. As has been outlined in many research articles, Cr(III)-based coatings exhibit poor corrosion resistance, combined with poor wear resistance and limitations on layer thickness when compared with Cr(VI)-based coatings, therefore effectively ruling out Cr(III) as an alternative to the Cr(VI)-based process. In order to overcome these performance gaps, different complexants and additives are utilised in Cr(III) baths for electroplating instead of Cr(III) salts. As a result, carbon and oxygen are often present in the coating with the chromium. The presence of carbon results in an amorphous structure and subsequently makes the coating more brittle. The effect of the trapped oxygen in the coating is the appearance of through cracks, the number and shape of which depend on the coating thickness. This is known as the dehydration phenomena and is the probable cause of the network of through cracks since the coating is more brittle.

One member reports the use of a Cr(III)-based bath using DURATRI-240, comprising of a trivalent chromium source, an organic complexant, and additives including a surfactant and a possible resin for bath treatment. It is noted by the member that for some materials, a sub-layer of either nickel or zinc could increase the ability to achieve the correct functionalities for a hard chrome plating, but that further investigative work is required, and it has been indicated that this would require new bath equipment and significant capital investment. They also report that the hardness of the Cr(III)-based plating is around 20% lower than that of the Cr(VI)-based coating, which can be acceptable depending on the utilisation of the coating (wear resistance will be lower with low hardness and the lifetime of the component will be reduced). However, they report that the hardness could be subject to change throughout the lifetime of the component due to the composition of the coating, whereby the hardness could increase following cycles of high temperature steps and result in hardness up to 30% higher than that of the Cr(VI)-based coating. Depending on the application, this can either allow a higher level of resistance (i.e., where there is one point of contact), or can cause wear to other components (i.e., continuous friction on another component). The increased hardness is due to the purity of the resulting metallic chromium layer, which can be >99% in Cr(VI)-based coatings, compared to around 90-94% for Cr(III)-based coatings. It is due to the carbon content in the chromium deposited layer from a Cr(III)-based process that this hardness increase is affected by temperature exposure. Heat treatment above 400°C results in the formation of chromium carbide, which has a high hardness and is problematic for components in contact with the chromium plated area due to chafing.

This member also reports that the formation of cracks appears during the chromium deposit build-up using the Cr(III)-based process. This is the influence of oxygen and carbon content in the chromium deposit, as described above. The wear index (WI) is also reported to be higher on Cr(III)-based coatings compared to Cr(VI)-based coatings (3-4 for Cr(III) compared to <2.5 for Cr(VI)). This corresponds to a reduced lifetime of the component if it is exposed to friction.

The timeline for the implementation of Cr(III) by the member is estimated to be TRL 4-5 by 2024, TRL 6 by 2025-2028, and TRL 7-9 by 2029-2032. However, different TRLs have been achieved depending on the substrate material to be plated and the geometry of the area to be plated, ranging from TRL 3 up to TRL 4-5 for some. This depends on whether the material to be coated requires anodic pickling with Cr(VI), as is the case with copper. For around 80% of the components plated by this company, anodic pickling is required. For the remaining 20% of components not requiring pre-treatment with anodic pickling, about 30% of these are "simple" components (e.g., easily plated racks and tools). These are sitting around TRL 4 but represent around 6% of the total quantity of components plated by this member company. On steel and stainless-steel substrates, progress remains at TRL 3.

The main challenge foreseen is the ability of the downstream supply chain to attain qualification of the alternative, and the timeline for these activities. However, they do foresee that by 2030, TRL 8 will be reached. It is noted that formal and written engagement of the OEMs would be required prior to preparation of the process line evolution from Cr(VI) to Cr(III), and in the meantime the qualification must be prepared by the companies using the plated components. This period is also used for production adjustment for quotations to customers. Another consideration within the implementation timeline is the requirement to install plating baths with specific material for fixturing and racks. The current steel baths for Cr(VI)-based plating contain iron, which are not suitable for Cr(III) baths, and so more R&D is required for the racks and tools to be used in the process. A new Cr(III) plating bath is currently being developed for this member, with the goal of avoiding oxygen and carbon contamination, however until this solution is suitably mature, progression will be blocked at TRL 3 for this member.

It is also noted by this member that for Part 145 (repair), it is unclear whether stripping of components without Cr(VI)-based treatments is possible, and whether the quality of the Cr(III)-based coating is sufficient when considering its susceptibility to grinding. As it stands, some repairs are not possible using Cr(III)-based treatments. It was clarified that Cr(VI)-based coatings are easy to remove and replace with chrome, meaning that during the maintenance activities carried out by this company components can be completely stripped and replated with chrome to make a new deposit. However, for Cr(III)-based coatings, stripping will depend on the utilisation of the component. Where the properties of Cr(III)-based coatings as mentioned above can vary with temperature, it can result in the inability to strip the coat effectively following these exposures. There is currently no experience of Cr(III)-based coat stripping following use on an in-service aircraft, only in a trial testing environment. More testing is required to overcome the difficulties with stripping of Cr(III)-based coatings; however, this is not seen as a priority.

Another member reports that their current Cr(III) plating process produced a micro-cracked chromium layer, which reduces corrosion protection by exposing the substrate material at the interface between the substrate and the plating. Moreover, a lack of adhesion is reported which would have a significant detrimental effect on products such as seal damage and foreign object damage, which could lead to a catastrophic failure of the product and the aircraft. Another company has ruled out trivalent chrome plating with heat treatment because of the high process temperatures required to obtain the minimum coating hardness and adhesion properties.

One member reports that Cr(III)-based electroplating is currently in development, at TRL 4 and not ready for serial applications.

Economic feasibility of Chromium (III) Plating

One of the major drawbacks to the replacement of Cr(VI)-based processes with Cr(III)-based plating is the production cost. Due to the process conditions requiring multiple chemical components, including organic chemicals in the electrolyte, compared to a simple combination of chromium trioxide plus sulphuric acid in the Cr(VI)-based plating process, the increased cost of production is a significant consideration in the substitution process. Moreover, the concentration of Cr(III) required in the bath is much lower compared to that required of Cr(VI) in the conventional process (0.4-0.5 mol L^{-1} of Cr(III) in the electrolyte compared to 2.5-3.0 mol L^{-1} of Cr(VI)). The consequence of the lower concentration of Cr(III) in the electrolyte is that replenishment of the bath solution would be required daily for the Cr(III)-based process, rather than the current weekly basis for Cr(VI). The presence of organic components for the formation of Cr(III) compounds in the plating bath is necessary to achieve reduction to metallic chrome (Cr(0)). If there is no aqueous medium, the Cr(III) will form a stable complex with water which will prevent the formation of Cr(0). It was also reported that the Cr(III) process is more sensitive to contamination, and so filtration is needed on a more regular basis to prevent this.

The difference in material for the anodes required in electroplating between the Cr(VI)-based process and the Cr(III)-based process will also be a consideration when it comes to substitution. Anodes used in the Cr(VI) process could be made of materials such as lead, normal steel or stainless steel. However, these materials would not be suitable for the Cr(III)-based process, which would require anodes made from stainless steel or graphite/carbide components. This would be sufficient for coating of simple components, but for those with more complex geometries, the anodes are reportedly unsuitable as they are less bendable and so it would not be possible to get anodes with specific shapes required for complex components without taking on the significantly higher cost of these anodes.

The Cr(III)-based process would incur higher energy costs due to the need to run the continuous filter system as described above, as well as requiring both heating and cooling equipment to maintain strict control of the bath temperature as needed for plating. The lower conductivity of the Cr(III) bath is also a factor effecting the energy required to plate a component, which would be higher than that for Cr(VI)-based processes while also requiring more time. It was estimated that the production cost of the Cr(III)-based process would be 200% higher for one company than the conventional Cr(VI)-based process, based on the scale up for production of chemicals and the optimisation required for the process implementation, and then would decrease gradually to around 140-150% of the original cost. Acceptance by the customers is usually linked directly to reduction in production cost for this company.

In summation, the direct challenges of substitution of Cr(VI) electroplating with Cr(III) electroplating formulations is the higher production cost and the requirements for additional investment in R&D. The production costs will increase due to the following impacts:

- **Raw material costs:** the price of raw materials for the potential candidate is higher than the price of the Cr(VI)-based formulation (i.e., chromium trioxide). There is a difference in material for the anodes required, which are more expensive than those currently in use. Additionally, the bath life of the alternative process is shorter, therefore a higher quantity of the potential candidate per annum (and hence per unit of production) is required;
- **Energy costs:** energy costs are expected to rise, especially due to the need to run the continuous filter system, as well as requiring both heating and cooling equipment to maintain strict control of the bath temperature, as needed for plating; and
- **Waste disposal cost:** the consequence of the lower concentration of Cr(III) in the electrolyte is that replenishment of the bath solution is required on a daily, rather than the current weekly

basis. This results in an increase in the volume of waste, and therefore disposal costs compared to current levels.

Another major barrier to substitution with the test candidate is the reduced performance level. Many members who carried out extensive R&D activities on substitution with Cr(III)-based electroplating suggest that the performance levels of the test candidate are lower compared to Cr(VI)-based electroplating. This leads to barriers related to the acceptance of alternatives by their customers. By way of example, for a DtB member, the main challenge for substituting is the wear and corrosion resistance of the test candidate being much lower than that achieved by the Cr(VI) process. Significant investments in R&D is required to improve the performance level of the test candidate. For small and medium-sized companies, which constitute about 50% of the ADCR members in the EEA, and more than half of UK-based members, such costs are a clear economic barrier to substitution. More time is required to ensure that they can be financed in a manner that does not impact their economic viability, hence, the potential candidate is not economically feasible.

Health and Safety considerations related to the use of Chromium (III) Plating

The CAS numbers for DURATRI 240 used in the Cr(III)-based electroplating process are listed in **Table 3-11** below.

Table 3-11: Composition of Cr(III)-based DURATRI-240 bath for electroplating		
Substance	**CAS**	**Note on hazards**
Chromium hydroxide sulphate	12336-95-7	Possibly skin sensitising, notified classification as eye irritant, harmful to aquatic life, skin irritant
Sulphuric acid	7664-93-9	Causes severe skin burns and eye damage
Ammonium formate	540-69-2	Notified classification as eye irritant, skin irritant and possible respiratory irritant
Sodium hydroxide	1310-73-2	Causes severe skin burns and eye damage
Potassium bromide	7758-02-3	Notified classification as serious eye irritant
ECHA 2022		

Availability of Chromium (III) Plating

One member reports that a transition phase would be necessary for running both Cr(VI) and Cr(III) baths for plating, especially for MRO activities, however they have identified a suitable supply chain for Cr(III) plating processes.

However, another company reports that at this time, there is no supply chain in place for Cr(III) plating solutions suitable for their needs, other than pilot lines established by suppliers involved in R&D projects. They estimate that process maturity must be developed before investing in production lines, and the demonstration of the change on the finished component must be validated by their end customers (which can take from 12-24 months). Following change approval and development of supplier production lines, a transition phase between 12 to 24 months will be necessary to secure procurements mainly on aircraft civil programmes with high production rate.

It was the position of at least one member that, whilst Cr(III) coatings would probably yield adequate coating performance, it was judged that a risk management option such as a restriction may be applied to Cr(III) in the EU in the future and therefore further research into this test candidate was not pursued.

Suitability of Chromium (III) Plating

For at least one member Cr(III) is identified as a test candidate for those components which will not be adversely affected by the heat treatment required to meet hardness requirements, however progression is still in the early stages of the substitution process and reliant upon the successful development and implementation of improved equipment. It is noted by another member that Cr(III) as an alternative to electroplating would not be acceptable on some components, where implementation would require the Design Office to create a brand-new design. There are also uncertainties about whether it would be possible to strip Cr(III) coatings where required for MRO. Further, a significant investment in additional equipment would be required to implement the Cr(III) plating process, whilst the ability of the supply chain to provide the plating solutions required for the process beyond pilot-line scale is also questionable.

3.5.8 Physical Vapour Deposition

3.5.8.1 Introduction

Physical vapour deposition (PVD) covers a variety of vacuum processes, all of which start with the coating material in a solid form. This is then placed in a vacuum or low-pressure plasma environment, to be vapourised and deposited onto the surface of a substrate in order to build up a thin film. The vaporisation step may be carried out via the following methods:

- **Vacuum evaporation:** the source material (i.e., the coating) is thermally vapourised in a vacuum and follows a “line of sight” trajectory to the substrate, at which point it condenses into a solid film. This method of vaporisation is used in applications such as mirror coatings and barrier films on flexible packaging (TURI 2006).
- **Ion assisted deposition/ion plating:** this method combines a film deposition onto a substrate, whilst ion plating bombards the deposit with energetic particles. These particles may be the same materials as the film or may be a different inert (argon) or reaction (nitrogen) gas. The ion beam assisted deposition describes a process in a vacuum environment, where the ions originate from an ion gun (TURI 2006).
- **Sputtering:** in this non-thermal vaporisation method, the surface atoms on the source material are physically ejected from the solid surface through transfer of momentum from bombarding particles. The particle is usually in gaseous ion form, accelerated from low pressure plasma or from an ion gun (TURI 2006).

PVD coating conditions are process specific and depend on the substrate and applied coating. The method is not generally limited by the substrate, however in practice, heat sensitive materials such as aluminium alloys and high strength steels are likely to be tempered due to the elevated process temperatures. Coating temperatures for PVD typically lie in the range of 180-450°C, but processes with lower and higher temperatures are also available. Coating times depend on various factors, such as coating thickness, spinning time of the component within the vacuum chamber, and the component geometry. The throughput of components generally depends on the size of the vacuum chamber and the component geometries.

Possible PVD coatings, applied either as a single or multi-layer, are based on materials including titanium nitride (TiN), titanium-aluminium nitride (TiAlN), zirconium nitride (ZrN), chromium nitride (CrN), chromium carbide (CrC), diamond-like carbon (DLC), silicon carbide (SiC), titanium carbide (TiC), and tungsten carbide (WC). DLC is a special coating consisting of combined bond types of graphite and diamond. It forms an amorphous diamond-like carbon layer with hardness properties > 2,000 HV.

PVD coatings consist of wear resistant, dense, and conformal layers generally considered to be very smooth, therefore they do not require further finishing processes. In some cases, the hardness is reported to be much higher than chromium, with lower coating thickness. **Table 3-12** below provides some properties of PVD coatings:

Table 3-12: Material properties of typical PVD coatings		
Materials	**TiN, TiAlN, ZrN, CrN, CrC, DLC, SiC, TiC**	
Properties	**Value**	**Note**
Hardness	1,200-2,400 HV	Dependent on material and internal stress
Maximum thickness	5µm	Up to 15µm in rare cases (high internal stress)
Corrosion resistance	Moderate	Limited by pinholes and sensitive to pitting
Wear resistance	Excellent	Better than chromium, wear life low, especially with low thickness
Stress and fatigue effect	Strongly thickness-dependent	In general, PVD coatings have very high comprehensive stress – fatigue usually adversely affected when coating thickness is above a few microns
Porosity	<1%	Limited by pinholes
Legg K., 2003a		

In addition to the mode of application, the material used in the process significantly influences the properties of the coating. The most promising materials for PVD coatings were reported to be WC-H, TiN, and CrN based on R&D carried out for the original Applications.

3.5.8.2 Status reported in original applications

Physical vapour deposition processes relate to the suspension of a coating material in a vacuum or low-pressure plasma environment. the material is then vapourised and directed onto the substrate in an atom-by-atom deposition process. This relates to the formation of a very dense, smooth and in an atom-by-atom deposition process. The process typically operates between 180-450°C and so may not be suitable for heat sensitive metals such as aluminium alloys or high strength steel substrates (CTAC Consortium, 2015).

It was reported that, due to the nature of the application, a maximum layer thickness of only 5µm can be achieved, well below the requirements for all the industry sectors. Whilst hardness is seemingly high, the thin nature of the coating means wear, and corrosion resistance failed to meet the requirements of the aerospace sector. It was concluded that in general, PVD coatings may be considered for niche applications but cannot be considered as a suitable alternative to functional chrome plating (CTAC Consortium, 2015).

PVD coatings are characterised by uniform layers with higher hardness compared to Cr(VI)-based coatings. PVD coating hardness ranges from 1,200 to 2,400 HV depending on the material coating, which exceeds the minimum requirement of 700-900 HV.

Compared to the stable coefficient of friction of less than 0.2 for metallic chrome plating, PVD coatings of tungsten carbide with amorphous carbon seems to meet the requirement. However, the coefficient of titanium nitride is too high.

Wear resistance of PVD was stated to be lower under high load for TiN and tungsten carbide with amorphous carbon. Concerns were reported regarding the wear performance, where PVD coatings were not deemed suitable for all aeronautic items, such as landing gears. However, some materials like WC-C-H showed sufficient performance in fretting wear conditions for specific applications under low load conditions because of self-lubrications and low friction coefficient. For copper alloy components, a wear rate of 6-10 mm^3/nm for up to 300,000 cycles is reported. Coatings of CoCrMo or Mo have sufficient wear properties against copper or steel substrates. Performance was five times higher in Taber testing than for metallic chrome coatings.

One of the limitations for the use of PVD coatings is evident in fatigue testing. Compared to metallic chrome coatings, the fatigue debit associated with PVD coatings such as WC-CH and TiN was tested and reported to be better for a number of substrates.

In terms of layer thickness, the typical thickness of PVD coatings is between 3 and 5µm which is well below the minimum requirement of 100µm in the aerospace industry. For carbide and nitride coatings, the thickness is limited due to the internal stress that occurs during application of the layer. As the stress increases with increasing coating thickness, PVD layers become brittle and tend to spall off when deposited in layers more than a few microns thick.

With respect to corrosion resistance, testing showed that WC-CH and TiN did not offer sufficient resistance because of the thin coating. Nitride coatings, despite being reported as essentially inert and non-corrodible, they do provide as much corrosion resistance as thicker metallic chrome coatings as they are thin and have an open columnar structure, particularly once they are damaged. PVD coatings did not generally achieve the corrosion requirements of the aerospace sector.

It was reported at the time of the original Applications that PVD coatings are only suitable for very specific applications, where only some of the critical performance parameters must be met. In general, PVD alternatives are mainly insufficient when it comes to fatigue, layer thickness and corrosion performance.

3.5.8.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Physical Vapour Deposition

One member reported that while PVD processes appeared to show promise as an alternative to hard chrome plating with Cr(VI) in some applications, they were ultimately set aside in favour of CVD processes.

Economic feasibility of Physical Vapour Deposition

One member reports that, although PVD is qualified for use by some industries, the process is long and expensive, with the coating chambers size limiting application and therefore availability. However, the process may be adequate for low loaded components.

Health and Safety considerations related to the use of Physical Vapour Deposition

There have been no detailed assessments reported for the use of PVD processes as an alternative to Cr(VI)-based electroplating at this stage. The coating is prepared in a closed system, so it is not expected that there is any exposure during use. The process eliminates the use of non-threshold carcinogens like chromium trioxide. It has been reported by one company that, if PVD is chosen for implementation as an alternative process, a full assessment of the hazards and risks related to its use will be carried out.

Availability of Physical Vapour Deposition

One company reports that the supply chain for PVD as an alternative process to electroplating with Cr(VI) is in place for new development projects. However, they note that on qualified products, the plating process must be approved by the design owner/customer through modification of relevant documentation (e.g., source control drawings, CMM, technical documents). Even if alternative processes are available, the company would only be able to change the actual process if approved by the design holder or type certificate holder.

Suitability of Physical Vapour Deposition

Due to the failure in wear and corrosion resistance, as well as insufficient layer thickness, this process was not considered a suitable alternative by the A&D industry in the parent AfA, and this remains the case for most members. Despite some promise shown in a single niche application since, due to the expense of the process it has been side-lined in place of chemical vapour deposition in this particular substitution project.

3.5.9 Plasma Spraying

3.5.9.1 Introduction

Plasma spraying is discussed using interchangeable terms such as “flame thermal spraying”, “thermal spray coating” and “plasma thermal spraying”, all of which indicate technologies where spraying of material onto a surface which gets melted or heated in the process. The process differs depending on the equipment used and the suitability for the application.

Plasma thermal spraying uses an arc as the source of heat, whereby a gas is ionised which melts and propels the coating material onto the workpiece. Thermal spray coatings can be based on flame, or a combustion process in which combustion gases are accelerated to supersonic velocities.

In the plasma spray gun (torch), the circulating gases are ionised by the arc formed between two electrodes. The plasma column is squeezed as it passes through the nozzle of the gun, and this energy concentration produces temperatures up to 15,000°C according to the nature and velocity of the gases (up to 1,000 m/s). This process is used to melt and spray appropriate materials – introduced in the plasma as particles – onto substrates to be coated or built-up with metal.

3.5.9.2 Status reported in original applications

The thermal spray process ionises gases to form highly energetic plasma which is used as a heat source capable of reaching 15,000°C. A coating material is injected into the plasma bean where particles are heated and directed towards the substrate surface. This process is similar to that of high velocity thermal processes although differs in the technology used and the coating microstructural properties (determined by the properties of the plasma stream) (CTAC Consortium, 2015).

It was reported that in general, plasma spraying resulted in a hard surface coating with good wear resistance and layer thickness, although this was dependent on the type of coating material used. As an example, a tungsten carbide coating typically results in hardness of 1,100-1,400 HV and wear resistance of 2-3x that of functional chrome plating. Despite these beneficial properties it was reported that plasma spraying results in a relatively poor-quality coating in relation to functional chrome plating. This was observed in high porosity of the plasma-based coating which related to increased permeability and lowered corrosion resistance. It was reported the process is also not very applicable for internal components as plasma spraying is a line-of-sight technology with complex equipment geometry (CTAC Consortium, 2015).

Compare to the conventional chrome plating method based on Cr(VI), the process of plasma spraying requires proper process definition and careful control, as well as highly trained and skilled workers. During hard chrome plating, the component to be coated is cleaned and masked, then left in the plating bath for a specific time which can vary significantly depending on applications (from 20 minutes up to 24 hours). With spray processes, large items are sprayed within minutes to hours. Small items can be sprayed in batches at the same time in special fixtures, thus plasma spraying is must faster but requires constant attention.

The layer thickness of a thermal spray coating can be readily applied up to 0.5mm, therefore it is suitable for repair and overhaul work on worn components. However, the quality of coatings are low compared to metallic chrome coatings, especially regarding porosity, which provides a reduced impermeability to the layer. Combined with the thinness of the layer, the susceptibility to corrosion is increased, and can be increased further with even thicker deposits on materials that are usually corrosion resistant materials due to porosity.

Bonding between the sprayed coating and the substrate is purely mechanical, whilst metallic chrome coatings adhere to the substrate according to solid-state physics. As adhesive strength to the substrate is potentially lower for plasma sprayed coatings than for metallic chrome coatings, in worst case scenarios flaking can result. Due to poorer quality coatings, plasma spraying is not used in high-pressure components.

Generally, plasma spraying is a line-of-sight process and unsuitable for components with complex geometry. For internal coatings, the opening diameter needs a minimum width of 40 mm for the plasma spray gun, however, to achieve the gun-to-substrate distance, a significantly larger diameter is required.

Performance of the plasma spraying process can vary for different coating materials. The substances which showed promising results at the time of the original Applications and/or were already applied in niche applications include tungsten carbide (WC-Co and WC-CoCr), CoCrMo and chromium carbide-nickel chromium (Cr_3C_2-NiCr). **Table 3-13** below provides example test results for a WC-Co coatings.

Table 3-13: Material properties of WC-Co plasma sprayed coatings

Property	Plasma spraying	Notes
Hardness	1,100-1,400 HV	Dependent on spray conditions
Thickness	500µm (0.5mm)	Normally limited by cost
Wear resistance (Taber test)	2-3 times compared to hard chrome plating	Smooth surface finish important
Legg K., 2003a & Holeczek 2011		

Plasma spray coatings range can reach a maximum layer thickness of 500µm; however, this is limited by costs and typically they reach a thickness of 200µm. As the minimum requirement for layer thickness in the aerospace industry is 100µm, plasma spray coatings exceed this. This makes it possible to use plasma spraying techniques for applications such as rebuilding of work components.

Plasma spray coatings generally display equal or even better wear resistance than metallic chrome coatings. CoCrMo or Mo coatings have sufficient sliding wear properties against copper or steel substrates, where performance is five times higher than for hard chrome plating.

The hardness of plasma spray coatings can achieve 1,100-1,400 HV, which meets the minimum hardness requirements for the aerospace sector. However, Mo and CoCrMo plasma sprayed coatings are softer with < 400 HV, which is only sufficient for specific applications with lower hardness requirements.

Corrosion resistance of plasma sprayed molybdenum coatings on steel and stainless steel were reported to be less than 72 hours salt spray test. Similar poor results were found for CoCrMo on steel, however on stainless steel could be increased to 750 hours when applied on a NiCr underlayer. However, layer thickness for thin coatings would not be fulfilled if an undercoat was needed, as the thickness then exceeds the maximum requirements.

Despite the requirements that can be met by plasma spray coatings, significant limitations persist. For example, where the geometry of the component is concerned, small or complex components are very difficult and sometimes impossible to coat.

Plasma coatings are porous, which can lead to an increased susceptibility to corrosion due to the reduced impermeability, made worse in combination with insufficient coating thickness. Additionally, the process temperatures are extremely high and exceed the threshold for heat sensitive substrates such as aluminium alloys, high strength and electrodeposited nickel components which become too soft and weak.

The suitability of plasma spraying must be checked for every component and application since performance varies for each substrate and material. the process is only suitable for specific niche applications. It was concluded that plasma spraying processes are not a technically feasible alternative for the replacement of conventional Cr(VI)-based electroplating processes in general applications and use in the aerospace sector.

3.5.9.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Plasma Spraying

One member using an internal measurement of technical readiness indicates that the plasma spray process for electroplating is at the equivalent stage to TRL 6. The member makes a general comment that for all treatments being investigated, there are none that could capture all requirements as provided by Cr(VI) treatments. In particular, it is difficult to achieve the appropriate standard of hardness. The member also reports that application temperature is difficult to achieve for plasma spraying.

Tribaloy[35] alternatives are described by at least one member, whereby Tribaloy 400 and Tribaloy 800 are two separate processes of plasma spraying coating. The difference between them lies in the chemical composition of the powder used for thermal spray coating. Problems experienced for rotor components plated with metallic chrome were reported, and include environmental issues, problems with chemical pitting from the coating process, arc-out damage, and hydrogen embrittlement with steel.

Tribaloy 400 is designed for exceptional wear properties in metal-metal contact scenarios at high temperatures. It has high cobalt and molybdenum content and high laves phase fraction resulting in very high hardness, with reasonable workability and a relatively lubricious surface due to the formation of molybdenum oxides at high temperatures.

[35] https://www.powderclad.com/products/specialty-powders/t400-t800-tribaloy-powders

Tribaloy 800 is designed for the highest possible service temperature in the alloy family, with operating capability nominally in the area of 1,000°C for certain environments. Tribaloy 800 replaces an additional 10 % of the cobalt content of Tribaloy 400 with chromium, adding protection against oxidation at the expense of some of the workability provided by high cobalt content.

The application of Tribaloy 400 and 800 are reported to have already been implemented on most components previously coated with hard chrome. However, there are still a certain number of components that cannot be coated with this process, and still require electroplating with Cr(VI).

One member reports that plasma spraying with Cr_2O_3 is qualified for certain applications, with limitations on its ability to meet all the required functionalities as well as Cr(VI)-based electroplating. These limitations are linked to the fact that the adhesion of the sprayed coating is not guaranteed on all alloy substrates. Limitations also include the technique's ability to coat internal diameters, where a maximum spray angle of 45° is specified by the design office in the application, as well as a specific diameter/length ratio (which was not defined).

Economic feasibility of Plasma Spraying

One of the limitations of plasma spraying techniques is that they require extensive current equipment for self-sustaining the arc current needed for creating the plasma. One member reports that the cost of implementing plasma spraying will be non-recurring costs such as new tooling to be created, followed by recurring costs such as raw materials for metal spraying.

Health and Safety considerations related to the use of Plasma Spraying

Tribaloy 400 and 800 are cobalt-based alloys in powder form containing the following elements:

Table 3-14: Elemental composition of Tribaloy 400 and 800 with chemical safety information

Element	% in Tribaloy 400	% in Tribaloy 800	CAS number	Properties of concern
Cobalt	58.4-62.5	49	7440-48-4	Carcinogenic Mutagenic (suspected) Toxic to reproduction Skin sensitising Respiratory sensitising
Molybdenum	27-26	28	7439-98-7	-
Chromium	6-9	17.5	7440-47-3	-
Silicon	2.2-2.6	3.5	7440-21-3	-
Iron	0.01-3	1	7439-89-6	-
Nickel	-	1	7440-02-0	Carcinogenic (suspected) Skin sensitising
ADCR Member (2022) *ECHA (2022)*				

Availability of Plasma Spraying

One member reports that a supply chain is in place for plasma spraying, but more (potentially full-scale) tests may need to be carried out if certain components require re-design.

Both Tribaloy 400 and 800 are commercially available and no issues are being reported in the supply chain or for stock availability.

Suitability of Plasma Spraying

One company reports that plasma spraying was not investigated as an alternative for hard chrome plating, and instead development was focused on HVOF coating.

However, another member reports that plasma spraying with Cr_2O_3 is already qualified for certain uses, with certification to be done in the classical change process component by component.

Based on the technical feasibility, economic feasibility and availability, plasma spraying represents one of the most promising alternatives to electroplating using Cr(VI). Despite this there are still clear limitations in its broad use across all components and substrates, and the presence of cobalt within both Tribaloy 400 and 800 creates some concern that transition to this alternative could represent a regrettable substitution.

3.5.10 General Laser and Weld Coating Technology

3.5.10.1 Introduction

General laser and weld coating process can encompass the following techniques:

- Laser alloying
- Laser cladding
- Electrospark deposition (ESD)/electrospark alloying
- Explosive cladding

These techniques are summarised as one group of alternatives as they are all based on the technology of weld coatings.

Laser alloying involved the integration of a material within an underlying surface. The difference between laser alloying and laser cladding are certain process conditions, for example the power and length of the laser pulse. During laser cladding, material such as metals and powder-form alloys or wires is fused onto the substrate surfaces to form a coating.

In an electrospark deposition system, material from a consumable electrode is transferred via an arc to the work piece. Almost any electrically conductive material is suitable as electrode material.

Explosive cladding is a cold process where the materials to be bonded are placed in close proximity and driven together with explosives. Suitable materials for this method include steel, wear resistant alloys, formable metals and some ceramic powders.

The material used in the process significantly influences the properties of the general laser and weld coating. The most promising materials for general laser and weld coatings were determined to be tungsten-carbide-cobalt (WC-Co) and chromium carbide-nickel (Cr_3C_2-15Ni).

3.5.10.2 Status reported in original applications

Laser alloying/laser cladding: laser cladding requires high surface temperatures above 500°C to weld the materials together. Heat treatment results in heat-affected zones underneath the coating layer, with increases serious risks of overheating, crack building and early fatigue. Because of the high temperatures and the risk of overheating, laser cladding is limited to materials that can handle the process temperatures. This technique is not suitable for general use, or for small or extensive coatings. The weld material tends to crack during multiple coatings because of the internal stress from the repeated high heat and cool cycles required to build up thicker layers.

For **electrospark deposition (ESD)** processes, the achievable layer thickness is strongly dependent on the coating material. For a coating material containing chromium carbide and nickel (Cr_3C_2-15Ni), layer thickness up to 250µm can be achieved. By contrast, WC-Co coatings are less conductive and are self-limiting in thickness with a maximum layer thickness around 25µm. The temperatures reached during the ESD process are below 1,000°C and are localised to an area which melts and leaves a heat-affected zone with a penetration depth less than 25µm. The heat-affected zone can lead to fatigue and corrosion issues caused by tensile stress, followed by cracks in the coating. Fatigue and cracking issues were the most critical concerns reported at the time of the original Applications.

The **explosive cladding** process does not involve heating, so dissimilar material such as aluminium and copper can be joined. It should be taken into account, however, that only material and components that can withstand the shock of the explosion are suitable for this process. Additionally, the layer boundaries between different materials display a wave structure due to the dynamics of the process. This can lead to degradation in the structure of the material, such as sub-surface crack growth and the fatigue debit which is generally a major problem of explosive cladding layers. Explosive cladding does produce thick coating layers greater than 6.4 mm, making the process suitable for rebuild and repair work. Using a metal or ceramic powder in the explosion rapidly compresses and solidifies into a solid layer. The porosity of the resulting coating is unknown.

General laser and weld coatings must conform to the shape of the surface being coated. Therefore, complex geometries with acute angles, edges and corners are difficult to coat, in some cases impossible. Therefore, explosive cladding was reported to only be suitable for simple shapes.

3.5.10.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of General Laser and Weld Coating Technology

One member reports that general laser and weld coating technology could only be used to address a limited scope of applications and would not be appropriate for all substrates. This member indicated that the technology is sitting around TRL 2 and is not suited to most steel substrates.

Economic feasibility of General Laser and Weld Coating Technology

The laser alloy/laser cladding process is not easy to handle as the process window between alloying and cladding is too narrow to obtain constantly reliable coating results on diverse components.

In ESD processes, the small size of the electrode allows only a small surface area to be coated and is too slow and expensive for use on large areas.

Health and Safety considerations related to the use of General Laser and Weld Coating Technology

The parent AfA reported an example of a coating material often used for laser and weld coating, which was classified in accordance with Regulation 1272/2008 (CLP) as: Skin Irrit. 2, Eye Irrit. 2, STOT SE 3, Carc. 2. This process therefore represents a less hazardous alternative to the use of chromium trioxide, a non-threshold carcinogen.

Availability of General Laser and Weld Coating Technology

No comments were received on the availability of general laser and weld coating technology.

Suitability of General Laser and Weld Coating Technology

Laser cladding is a line-of-sight process and so is not suitable for extensive coatings or components with complex geometries. Laser cladding is especially unsuitable for use in overhaul and repair activities. Laser and welding processes are therefore not considered appropriate as replacement processes for hard chrome plating.

3.5.11 Stainless Steel and High-Speed Steel

3.5.11.1 Introduction

Stainless steel is an alloy with at least 11 % chromium content by mass. They contain sufficient chromium to form a passive film of chromium oxide, which can protect the surface from corrosion by blocking oxygen diffusion to the steel surface. It also blocks corrosion from spreading into the internal structure of the metal. Steel and oxide ions are similar in size, and they bond very strong and remain attached to the surface. As an alternative to metallic chrome coatings, stainless steel could be used as cladding tube on components such as piston rods. A tube is used as a covering liner that protects the substrate surface.

There are no standards or definitions that cover high speed steel processes. High speed steels are multi-component alloys containing tungsten, chromium, molybdenum, vanadium, cobalt, niobium and carbon with a higher than 0.6 % weight. Alloys are transformed by an appropriate heat treatment process to high-speed steels. Varying elemental weight percentages are categorised as follows:

- Normal steel: ≤ 8 %
- Semi-high speed steels: > 8-12 %
- High speed steels: > 12 %

3.5.11.2 Status reported in original applications

In the original Applications, the intrinsic corrosion resistance of some stainless steels with lower requirements was reported to be sufficient. For example, stainless steel 15/5 PH was required to resist 2 hours in a specified salt spray test in the aerospace industry. Stainless steel does not protect against galvanic corrosion. Therefore, additional surface treatment is required to provide this functionality. It was also reported that wear resistance, coefficient of friction and hardness performance of high-speed stainless steels were not sufficient. The hardness performance of stainless steel was not sufficient and often required additional treatment such as carburising.

R&D activities carried out at the time of the original Applications were ceased as a result of the inability of high-speed steel to meet the critical functionalities. In the aerospace sector, the use of stainless steel is critical as it is a lightweight material.

3.5.11.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Stainless Steel and High-Speed Steel

One member reports that stainless steels are used as a valid alternative to the combination of low alloy steels and chromium plating for new development projects. However, during maintenance activities, hard chromium plating is still required for the repair of worn diameters.

Economic feasibility of Stainless Steel and High-Speed Steel

It has been reported that, due to the significant technical failure of stainless steel and high-speed steel, no quantitative analysis of economic feasibility has been conducted.

Health and Safety considerations related to the use of Stainless Steel and High-Speed Steel

Since this alternative is not deemed technically feasible, and as stainless steel defines a diverse family of alloys, the exact composition of a potential alternative cannot be known. However, it could be assumed that stainless steel would be a less hazardous substance than chromium trioxide.

Availability of Stainless Steel and High-Speed Steel

No comments were received on the availability of stainless steel and high-speed steel.

Suitability of Stainless Steel and High-Speed Steel

As indicated above, whilst the use of stainless and high-speed steel may be suitable for some new development projects, like any other potential substrate substitution it is not a viable option for MRO activities on legacy parts.

3.5.12 Thermal Spray Coatings

3.5.12.1 Introduction

Thermal spray coatings cover four general types of thermal spray in order of increasing coating quality:

- Flame spraying (including wire flame spraying, powder flame spraying)
- Cold gas spraying
- (Wire) arc spraying
- HVOF

As Plasma spraying and HVOF are discussed in Sections 3.5.9 and 3.5.6, this Section discusses flame, arc, and cold gas spraying processes as a group, referred to as "thermal spray processes".

Wire arc spraying involves an electric arc serving as both the heat source and as a source of molten metal droplets that are transported via a gas jet to the substrate surface.

In **cold gas spraying,** the coating particles are accelerated to a high speed via ultra-high velocity gas stream. As the particles heat the surface, they soften and melt through a conversion of kinetic to thermal energy. At the time of the original Applications, cold gas spraying was only deemed suitable for depositing low melting point metals such as copper and aluminium and was not feasible for serial production. Moreover, the process was still limited to ductile materials such as aluminium, stainless steel, titanium, and alloys.

Flame spraying is a simple thermal spray method suitable for lower quality alloy coatings, where the coating powder is injected into a gas jet and fed through a flame. Compressed air atomises the molten metal and accelerates the particles onto the substrate. The coating is generally of low quality, being porous and exhibiting low adhesion, therefore it is not suitable as an alternative to hard chrome plating.

Aside from the mode of application, the properties of the thermal spray coatings are significantly influenced by the material used in the process. The most promising materials for thermal spray coatings are reported to be WC-Co, WC-Co-Cr and WC-Cr-Ni.

3.5.12.2 Status reported in original applications

As a line-of-sight process, thermal spray processes are not suitable for components with complex geometries. The size of the gun, constitution and the spray angle are limiting factors. Thermal spray processes involve both thermal and kinetic energy, which are focussed and allow the particles to reach temperatures above 2,500°C. As a consequence, the substrate is heated up specifically at the superficial layers. Overheating is a serious risk, as is crack building and early fatigue. This is due to the degradation of substrate properties when influenced by heat. Thermal processes are therefore limited to substrate materials that can withstand high process temperatures.

As thermal spraying is conducted in air, an oxide will form as the molten particles are accelerated towards the substrate. The presence of oxides raises the porosity and brittleness of the layer, lowering the bonding strength. hardness is affected and was reported to be in the range of 400-700 HV for tungsten carbides, which is below the minimum hardness requirements of the aerospace sector.

Coating particle sizes set a practical lower limit to the layer thickness, which is approximately 25µm. The upper limited was reported to be 20 mm. As surface treatment is needed after coating to obtain a smooth, closed surface, a thicker sprayed coating is required and must be resized by post-treatment.

Corrosion resistance provided by arc sprayed coatings is approximately 50 % lower than that provided by metallic chrome coatings because of the layer porosity and brittleness. The process has a cycle time at least ten times greater than functional chrome plating. It is therefore considered to be suitable only for low volume production.

3.5.12.3 Progression reported by ADCR Members

Technical feasibility/Technical Readiness Level of Thermal Spray Coatings

As a line-of-sight process, thermal coating is not suitable for components with complex geometries. Thermal processes are also limited to substrate materials that can withstand high process temperatures.

Economic feasibility of Thermal Spray Coatings

It has been expressed that there are concerns regarding the replacement of Cr(VI)-based electroplating with thermal spray coatings, as they require a large investment to set up the infrastructure needed until such as time as design authorities agree on the process that will meet their design needs. It is assumed that the thermal spray coating process is generally more expensive than hard chrome plating, whether it is performed internally or at a subcontractor level.

Health and Safety considerations related to the use of Thermal Spray Coatings

The parent AfA reported an example of a coating material often used for laser and weld coating, which was classified in accordance with Regulation 1272/2008 (CLP) as: Skin Irrit. 2, Eye Irrit. 2, STOT SE 3, Carc. 2.

Availability of Thermal Spray Coatings

The parent AfA reported that commercial arc guns are used for specific niche A&D applications but are not a general alternative to functional chrome plating. Cold gas spraying was reported not to be commercially available and flame spraying, while commercially available, was also not considered a general alternative to functional chrome plating.

ADCR members did not report any further progression with this process.

Suitability of Thermal Spray Coatings

One company reports that wire arc spraying, and flame spraying, were considered as alternatives for hard chrome plating, but were ultimately rejected in favour of HVOF coating. However, they are currently under active consideration for repair activities, where thermal spray coatings have been successfully implemented to replace electroplating with Cr(VI) on a significant number of components during repair activities. However, this is more difficult for a number of components, and more time is required to consider and test a range of solutions.

3.6 Conclusions on shortlisted alternatives

The table below summarises the current development status of Cr(VI)-free test candidates for electroplating.

Table 3-1516: Current development status of Cr(VI)-free test candidates for electroplating

Alternative	Technical feasibility	Economic Feasibility	Risk reduction	Availability	Suitability
Electroless Nickel plating	Moderate	Moderate	Low	Moderate	Moderate
Nickel/nickel alloy electroplating	Low	Moderate	Low	Moderate	Low
Case hardening	Low	Moderate	Low	Low	Low
Chemical vapour deposition	Moderate	Moderate	High	Low	Low
Nanocrystalline Cobalt-Phosphorous alloy coating	Moderate	High	Low	Low	Low
High velocity thermal process	Moderate	High	High	Moderate	Moderate

Chromium (III) plating	Moderate	Moderate	Moderate	Moderate	Moderate
Physical vapour deposition	Low	Low	High	Moderate	Low
Plasma spraying	High	Moderate	Low	High	High
General laser and weld coating technology	Low	Moderate	High	Moderate	Low
Stainless steel and high-speed steel	Low	Moderate	High	Low	Low
Thermal spray coatings	Low	Moderate	High	Low	Low

There is no single process which represents the most promising option from the shortlisted alternatives, as the most suitable alternatives will differ between ADCR members depending on the substrate, geometry and size of the components to be treated. Further research and additional progress is reported for all but two of the shortlisted alternatives (nano-crystalline cobalt-phosphorous alloy coating, and physical vapour deposition) since the original applications, whilst some members are actively pursuing multiple alternatives where a single solution does not exist across all parts currently using Cr(VI) electroplating. A number of the above proposed candidates are therefore represented across the members' substitution plans, however due to the current level of development, the technical obstacles, and the complexity of the substitution process described in section 3.1.2, none can be implemented for all components and final products prior to the end of the existing review period.

3.7 The substitution plan

3.7.1 Introduction

3.7.1.1 Factors affecting the substitution plan

The substitution plan is impacted by a combination of factors affecting the implementation of the alternative, these include:

- Functionality, and ability to meet performance requirements (technical feasibility);
- Availability, and suitability of the alternative;
- Process changes such as equipment, training, health and safety (*Technical challenges and economic feasibility*);
- a substitution process which is subject to regulatory control, legal constraints, and customer requirements;
- Economic feasibility, including the capital and operational costs of moving to an alternative and the costs of implementing the alternative across the supply chain; and
- Progress and alignment with other REACH substitution workstreams.

Each factor will contribute to the achievement of milestones that must be met to realise delivery of the substitute(s) to Cr(VI) for electroplating, and its relevant pre-treatments. They require continuous review and monitoring to ensure that the substitution plan progresses through its phases and all changes are clearly documented. Monitoring of progress markers associated with the substitution plan includes a timetable of steps and targeted completion dates, assessment of the highest risks to progression, and how these risks can be reduced (if possible), which may not always be the case.

3.7.1.2 Substitution plans within individual members

Each ADCR member has a substitution plan to remove Cr(VI) in electroplating that is uniquely reflective of their individual situation. Additionally, an individual member often has multiple substitution plans for electroplating, running in parallel work streams. The reason for different substitution plans within one member is that they are segmented by factors such as type of substrate, type of component, and type of alternative. These different substitution plans are progressed simultaneously although they typically have differences in timing of milestones and anticipated achievement of each TRL/MRL level, based on various factors such as the technical difficulty of introducing the alternative and prioritisation of certain types of component or substrate.

3.7.1.3 Interplay with pre-treatments

Development of substitution plans for alternatives to Cr(VI) for electroplating are fundamentally related to and impacted by the pre-treatment. In the case where members are using Cr(VI) in the pre-treatment, they develop the Cr(VI)-free pre-treatments in parallel with the Cr(VI)-free electroplating. The progression and success of the development of alternatives to Cr(VI) in electroplating depends on the successful development of pre-treatment alternatives. Any unexpected technical failures in the development of the pre-treatment will impact the planned timing of the substitution plan for the electroplating.

In some cases, a member will target substitution of Cr(VI) from both the pre-treatment and the electroplating at the same time.

3.7.2 Substitution plan for ADCR in electroplating

3.7.2.1 Substitution plans

Multiple test candidates to replace Cr(VI) in electroplating have been investigated by members, and have been progressed to various stages, with variation arising from different types of components and substrates.

The expected progression of ADCR members' substitution plans to replace Cr(VI) in electroplating is shown in **Figure 3-6** below. The progressive stages of the substitution plan (development, qualification, validation etc.) as shown in the diagram are described in detail in section 3.1.2. Implementation and progression of substitution plans ultimately leads to reduced Cr(VI) usage. MRL 10 is the stage at which manufacturing is in full rate production and is therefore where significant reduction in Cr(VI) use due to replacement with an alternative is expected.

The data in **Figure 3-6** show the expected progress of 50 distinct substitution plans for Cr(VI) in electroplating, covering different plans across different members, and also multiple plans within individual members. These data have been aggregated to present the expected progress of the substitution of Cr(VI) from electroplating for the ADCR consortium as a whole.

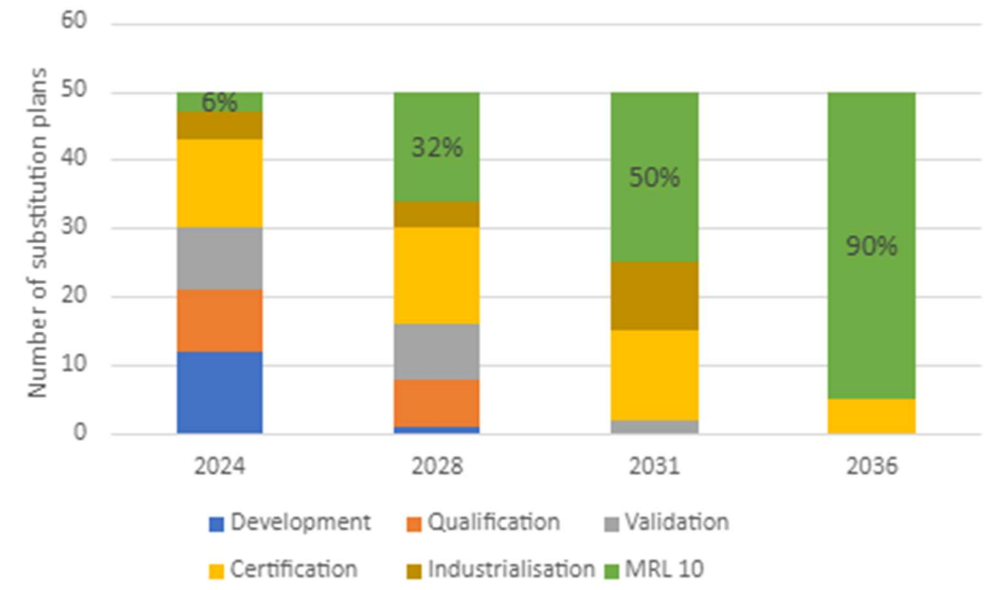

Figure 3-6: Expected progression of substitution plans for the use of Cr(VI) in electroplating, by year
The vertical axis refers to number of substitution plans (some members have multiple substitution plans for electroplating). The percentage value shown on each of the green bars indicates the proportion of substitution plans that are expected to have reached MRL 10 by the date indicated. MRL 10 is the stage at which there is expected to be a significant reduction in Cr(VI) usage.
***Source:* RPA analysis, ADCR members**

The above summary shows:

- Variation in the status of different substitution plans in each of the years (this variation is due to issues such as technical difficulty (including consequential compatibility issues), type of substrate, type of component); and
- Expected progression in future years as an increasing proportion of the substitution plans reach MRL 10

The dates at which each substitution plan is expected to achieve each stage are estimates provided by the members, and there are uncertainties due to, for example, unexpected technical failures which may only reveal themselves at more advanced stages of testing. Consequently, the expected progress of substitution plans, especially in the outer years 2031 and 2036 where there is more uncertainty, may be slower (or faster) than estimated today, as presented in **Figure 3-6**. The actual status of the substitution plans 12 or more years from now could be different to our expectations today.

Because many members have multiple substitution plans for electroplating, it is the case that for those substitution plans that are not expected to have achieved MRL 10 by a given date, other substitution plans from the same member will have progressed to this level. This highlights the complexity of multiple substitution plans within members resulting from differences in, for example, type of substrate, type of component and type of alternative being developed.

There are many issues that limit members' progression of the substitution plans beyond the stages indicted in **Figure 3-6.** Technical issues include for example technical failures on some types of component or substrate (failure to meet hardness, wear resistance, friction, or layer thickness issues), inability to meet performance requirements set out in customer specifications, and significant process limitations on components with complex geometry (some of the alternatives are sprays which rely on line of sight and so cannot coat complex shapes or internal diameters, which would result in performance and quality issues). Process issues include for example the requirement for approval from a wide range of customers in a wide range of component uses (which requires extensive and time-consuming testing), and the need for a phased transition by product line. Additionally, some of the alternatives to Cr(VI) for electroplating are a completely different type of process, with significant engineering changes needed to the existing systems or the need to build a completely new line where the old line cannot be re-purposed for the new technology. Running both the old and new process in parallel is not practicable due to, for example, limitations on floor space and in these cases transition to the Cr(VI)-free process will need to wait until all relevant substitution plans have reached the appropriate stage.

The timeframes associated with the activities presented in **Figure 3-6** result from the requirements of the substitution process, which are presented in section 3.1.2. To be noted also is that approval of suppliers cannot always occur in unison; qualification may need to cascade down the supply chain depending upon the number of tiers and actors involved. As resources are not available to action this simultaneously across all suppliers, the timescale for supplier qualification may be extended. Modifications may be required to the supply chain to allow for the installation of new equipment in some cases, although this can be mitigated by sourcing from existing established suppliers familiar with the requirements of qualification protocols.

3.7.2.2 Requested Review Period

It can be seen in **Figure 3-6** that despite ongoing and concerted efforts of the members to develop alternatives to Cr(VI) in electroplating, it has not proved possible to replace Cr(VI) by the end of the Review Periods granted in the parent Authorisations (which end in 2024). It is clear from the chart that in 2031 (equivalent to seven years beyond the expiry date for the existing authorisations), while many substitution plans are expected to have successfully progressed to MRL 10 and the consortium is expected to have reduced its Cr(VI) use, an equally significant proportion (half of the total substitution plans) are not expected to have achieved MRL 10 and are expected to be predominantly at the certification or industrialisation stages. For these substitution plans (which are from several member companies), there is still expected to be a need for the use of Cr(VI).

As a result of the individual members' substitution plans summarised above, **the ADCR requests a Review Period of 12 years for the use of Cr(VI) in electroplating**.

4 Continued Use Scenario

4.1 Introduction

Section 3 provided an analysis of the alternatives with respect to the technical feasibility, economic feasibility, availability and suitability of alternatives. The assessment highlights the importance of Cr(VI) in providing wear resistance, hardness and the other key functions highlighted, on substrates including (but not limited to) aluminium (and its alloys), steel (including stainless steel), nickel and other alloys. Some companies already use Cr(VI) alternatives in electroplating such as Cr(III), however these alternatives are not implemented across all uses of electroplating due to both technical and economic feasibility issues.

Until alternatives which are also compatible with pre- and post-treatment steps as relevant, and which deliver an equivalent level of functionality on all substrates are tested, qualified, validated and certified for the production of components and products, use of chromium trioxide in electroplating will continue to be required; the use is essential to meeting airworthiness and other safety requirements. Even then, issues may remain with legacy spare parts and maintenance where certification of components using alternatives is not technically feasible or available due to design control being held by MoDs, who will not revisit older designs in the near future.

In some cases, alternatives are technically qualified and certified, but time is needed to industrialise and implement them across all industrial sites in the value chain. Given the significant number of BtP suppliers involved in the use of electroplating, implementation itself may take several years (e.g., 6-8 within the larger value chains).

As a result, as demonstrated by the substitution plan, the OEMs and DtBs - as design owners - require between seven and 12 years to complete substitution across all components and final products.

The continued use scenario can be summarised as follows:

Continued use of Cr(VI) in electroplating whilst substitution plans progress	Continued use for production, repair and maintenance of parts and components
-> R&D on substitutes and progression to MRL 10 continues, with substitution plans aiming to be at MRL 10 by 2036	-> A&D sector retains and expands its EEA / UK manufacturing base
-> Downstream use continues in A&D supply chain as alternatives are certified and implemented	-> Industrialisation of substitutes and their adoption across supply chains
->Modification of designs as substitutes, are certified and industrialised	-> R&D into the adoption of more sustainable technologies continues
-> Update of Maintenance Manuals to enable substitution in MRO activities	-> Employment in the sector is retained while worker exposures and risks decline over time
-> Continued production, repair and maintenance of aircraft and other final products ensured	-> Impacts on civil aviation, emergency services and military mission readiness is minimised

The remainder of this section provides the following supporting information to describe the Continued Use Scenario:

- The market analysis of downstream uses in the A&D markets;
- Annual tonnages of chromium trioxide used in electroplating, including projected tonnages over the requested review period;
- The risks associated with the continued use of chromium trioxide.

4.2 Market analysis of downstream uses

4.2.1 Introduction

The A&D industry has separately and jointly assessed, and continues to review, its needs to ensure:

- the ability to carry out the specific processes required to manufacture, maintain and repair A&D components and products in the EEA/UK; and
- continuity of supply of critical products containing hexavalent chromium.

The requirements of the ADCR members – as downstream users - supporting this application have been carefully identified and analysed, taking as the starting point the parent authorisations and the substance-use combinations covered by these. Over the lifetime of the ADCR consortium, the number of uses identified as requiring authorisation and the number of OEMs and downstream users supporting each use has decreased (including the individual chromate substances involved in a use), to ensure that authorisation is only sought for those cases where there is no substitute that is fully qualified as per stringent airworthiness requirements and industrialized by all members and their supply chains. The continual re-visiting of supply chain requirements fed into the narrowing of the substance-use combinations requiring re-authorisation compared to the original applications for authorisation. This has led, for example, to sodium dichromate no longer being supported for authorisation in electroplating because members and their supply chains have been able to eliminate its use in the EEA and UK.

Furthermore, the scope of this application is driven by A&D qualification, validation and certification requirements, which can only be met by use of the substances/formulations that provide required performance that is mandated by airworthiness authorities. This constrains OEMs and hence their suppliers and MRO facilities to the use of chromium trioxide in electroplating until alternatives can be qualified and certified across all of the relevant components. In many cases, the choice of substances and mixtures to be used is further affected by the fact that they form part of a process flow (see **Figure 2-2**), which has been developed over time to meet specific performance requirements as part of ensuring airworthiness.

4.2.2 Overview of the European aerospace and defence sector

In 2020, the European A&D industry comprised over 3,000 companies of all sizes and employed over 880,000 highly skilled employees (with these figures including the UK[36]). As noted by the European Commission, the industry is "characterised by an extended supply chain and a fabric of dynamic small-and medium- sized enterprises throughout the EU, some of them world leaders in their domain"[37]. **Figure 4-1** provides details of turnover and employment for the industry in 2020, based on the Aerospace, Security and Defence Industries Association of Europe (ASD) publication "2021 Facts & Figures".[38]

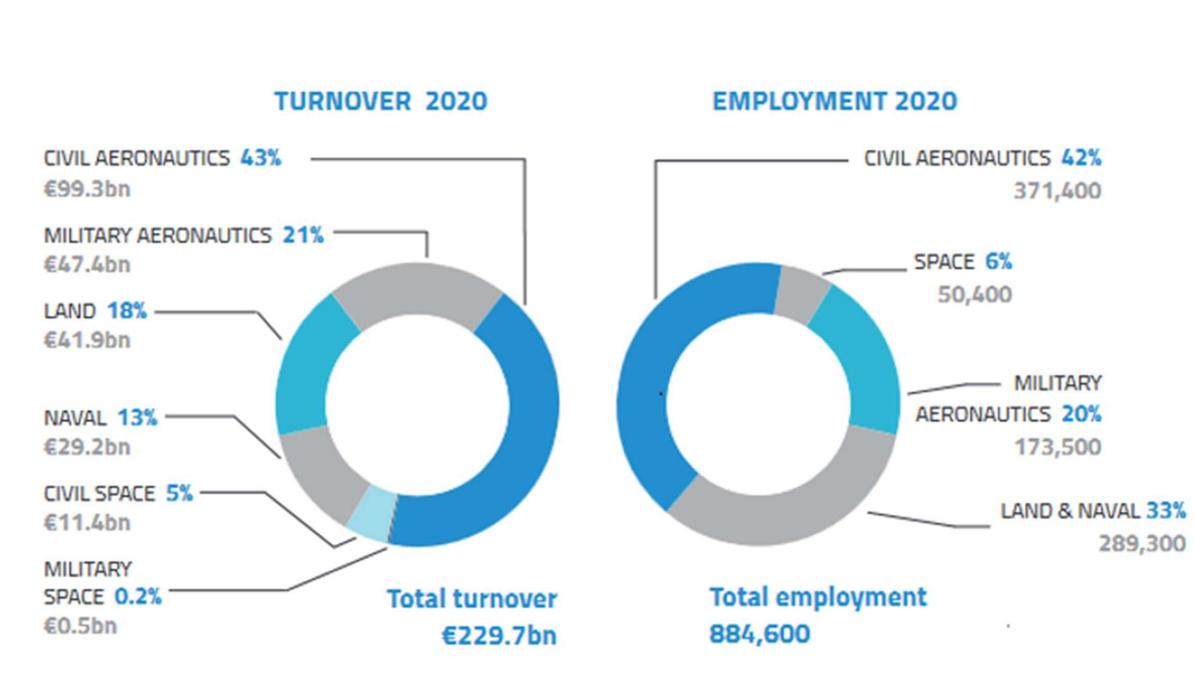

Figure 4-1: Turnover and Employment for the European Aerospace and Defence Industry in 2020
Based on ASD, 2021, available at: https://www.asd-europe.org/sites/default/files/atoms/files/ASD_Facts%26Figures_2021_.pdf

As can be seen from **Figure 4-1**, civil and military aeronautics alone accounted for 64% of turnover and 75% of employment for the sector in 2020.

Civil aeronautics alone accounted for over 370,000 jobs, revenues of over €99.3 billion and exports of €88.3 billion. Note, these figures are lower than those for 2019, reflecting the impacts of COVID-19 on the sector. For example, the 2019 figures for civil aeronautics were around 405,000 jobs and €130 billion in revenues, with exports amounting to around €109 billion.

The defence industry accounted for around 462,000 jobs, revenues of over €119 billion and exports of €45.6 billion. These figures reflect reductions in exports, employment and revenues compared to 2019, stemming from the impacts of COVID-19 on the sector.

The A&D sector is therefore recognised as important to the ongoing growth and competitiveness of the EEA and UK economies. It is also recognised that both require long-term investments, with aircraft and other equipment being in service and production for several decades:

- Aircraft and other A&D products remain in service over long time periods. For example, the Boeing 747 first entered service in 1970, and continues to be flown and produced in 2022 (although it will now go out of production but remain in service). Given the need to ensure

[37] https://ec.europa.eu/defence-industry-space/eu-aeronautics-industry_en

[38] ASD, 2021: Facts & Figures, available at: https://www.asd-europe.org/facts-figures

on-going airworthiness and due to certification requirements, there will continue to be a "legacy" demand for the use of chromium trioxide in the production of components for maintenance of existing aircraft and equipment, as well as for models that are still in production long periods after the first aircraft or military products were placed on the market;

- A&D technologies take many years to mature. Product development is a five- to ten-year process, and it can take 15 years (or more) before the results of research projects are applied in the market. As part of the development and roll-out of new A&D products, OEMs must be ready to demonstrate fully developed technologies, or they risk losing contracts that may have a lasting effect on business.[39]

- The long product development process applies not only to the introduction of new technologies, but also to any activities aimed at adapting existing technologies as required for the substitution of chromium trioxide As indicated below with respect to R&D activities, research on substitution of chromium trioxide has been underway for several decades, with the substitution of chromium trioxide in electroplating processes proving one of the most difficult tasks, in part due to its process flow (see **Figure 2-2**) and relationship with other surface treatments.

- There are over 20,000 commercial aircraft and 15,000 business jets currently in operation globally. Given the global nature of civil aviation, it is important that global solutions are found to the use of chromium trioxide, in particular with respect to maintenance, overhaul and repair operations (MRO). Actors involved in MRO activities must adhere to manufacturers' requirements and ensure that they use certified components and products. They have no ability to substitute away from chromium trioxide where these are mandated by the original equipment manufacturers.

4.2.3 Economic characteristics of companies undertaking electroplating

4.2.3.1 Overview of Uses and Downstream Users

Electroplating is one of the most supported uses of CT by the ADCR. The process is relevant to production, repair, maintenance and overhaul of a range of aerospace components. Components mentioned within the SEA questionnaire include but are not limited to:

- Weapon barrels
- Mechanical fastenings
- Dynamic components
- Engine shaft
- Body valve
- Turbine disc
- Sleeve valve, and
- Landing gear.

Additionally, electroplating treatments are used to ensure reliability, longevity, and precision for use in gun barrels for defence purposes.

[39] ATI (2017): The Economics of Aerospace: The Economic Impacts of UK Aerospace Industrial Strategy.

37 companies, operating over 68 sites, responded to the SEA questionnaire confirming that CT was used for electroplating in A&D uses. The size distribution of these companies is shown in **Table 4-1** (note that the columns total 45 due to some companies operating in both the EEA and UK). As would be expected by the composition of the ADCR, respondents to the SEA survey tended to be the medium and larger sized companies within their sectors of activity.

Table 4-1: Numbers of SEA respondents undertaking electroplating

Company size	EEA	UK
• Micro	1	2
• Small	5	4
• Medium	8	4
• Large	14	7
• Total	28	17

4.2.3.2 Economic characteristics

Table 4-2 provides a summary of the number of companies identifying their activities against different NACE codes, which are used here to develop the economic characteristics of the "typical" OEM, DtB, BtP or MRO company. Companies may have indicated more than one NACE code as being relevant to their activities, such that the number of relevant NACE code counts is higher than the number of SEA responses relevant to electroplating alone. It is notable that most companies identified "treatment and coating of metals" as a relevant NACE code, while at the same time identifying other relevant codes.

The table also provides relevant Eurostat data for each code on turnover (weighted average provided here, based on % of respondents by company size), Gross Value Added (GVA) per employee, average number of employees, and average personnel costs per employee.

Turnover is calculated as the weighted average by company size, as this is the most appropriate means of reflecting the level of turnover across the EEA (including UK) linked to electroplating treatments and taking into account the size distribution of the companies[40] that are involved in such activities. GVA per employee, numbers of employees, and average personnel costs are generally given as the sector average and not per company size for several of the NACE codes, so it was not possible to calculate weighted averages for these. Note that the count total is by company and not by site.

[40] Microenterprises have been excluded from the turnover calculations as very few such enterprises will be acting as key suppliers within the supply chain. The calculations taken into account the percentage of turnover for each relevant sector attributed to small, medium and large companies to derive the average weighted per site by role figures used in these calculations.

Table 4-2: Economic characteristics of "typical" companies by NACE in sectors involved in Electroplating (2018 Eurostat data, covering the EU 28)					
	Number of responses by NACE code	Weighted average turnover per company € million	GVA per employee €	Average personnel costs per employee €	Average GOS as a % of turnover
C2561 - Treatment and coating of metals	29	20.88	54,000	35,500	15.5%
C2540 - Manufacture of weapons and ammunition	1	306.44	70,000	42,500	12.3%
C2594 - Manufacture of fasteners and screw machine products	2	57.20	65,000	43,200	9.7%
C2599 - Manufacture of other fabricated metal products n.e.c.	4	57.20	65,000	43,200	9.7%
C265 - Manufacture of instruments and appliances for measuring, testing and navigation;	2	159.30	84,000	57,500	11.1%
C2732 - Manufacture of other electronic and electric wires and cables	1	34.39	76,000	51,700	4.8%
C2815 - Manufacture of bearings, gears, gearing and driving elements	4	284.64	72,000	44,500	7.9%
C3030 - Manufacture of air and spacecraft and related machinery	7	1,214.65	98,000	76,400	11.2%
C3040 - Manufacture of military fighting vehicles	4	1,214.65	99,000	64,800	9.8%
C3316 - Repair and maintenance of aircraft and spacecraft	13	71.33	85,000	56,400	8.4%
Other	1	NA	NA	NA	NA
Total count	68				
Note: The count total is by number of NACE code identifications by company and not by sites, with 37 companies providing data					

Turnover is calculated as the weighted average by company size, as this is the most appropriate means of reflecting the level of turnover across the EEA (including UK) linked to electroplating treatments and taking into account the size distribution of the companies[41] that are involved in such activities. GVA per employee, numbers of employees, and average personnel costs are given as the sector average and not per company size for several of the NACE codes, so it was not possible to calculate weighted averages for these. Note that the count total is by company and not by site.

Data on Gross Operating Surplus[42] as a percentage of turnover (the GOS rate) is also used here to provide an indication of the profits associated with the turnover generated by these sites. This is based on a figure of 11% which is an average across the various NACE codes weighted by the number of companies declaring each NACE code.

As can be seen from **Table 4-3**, the 68 sites (operated by the 37 companies) for which data were collected via the SEA questionnaire represent an estimated €34.3 billion in turnover and almost €3.8 billion in GOS as a proxy for profits. Across all 150 sites (125 in the EEA and 25 in the UK) calculated as undertaking electroplating, these figures rise to almost €44.4 billion in turnover and €4.9 billion in GOS.

Table 4-3: Key turnover and profit data for market undertaking electroplating (based on 2018/2019 Eurostat data)

Sites covered by SEA responses/ Extrapolated number of sites	Estimated turnover based on weighted average € million	Gross operating surplus (estimate based on 10.5%) € million
55 EEA Sites	25,390	2,793
13 UK sites	8,897	979
Extrapolation to all sites involved in chromate-based electroplating in the EEA or UK		
125 EEA sites	33,567	3,692
25 UK sites	10,822	1,190
Source: Based on SEA questionnaire responses, combined with Eurostat data		

4.2.3.3 Economic importance of electroplating to revenues

Electroplating will only account for a percentage of the calculated revenues, GVA and jobs given in the above table. To understand its importance to the activities of individual companies, a series of questions were asked regarding production costs, and the share of revenues generated from the use of chromium trioxide.

41 Microenterprises have been excluded from the turnover calculations as very few such enterprises will be acting as key suppliers within the supply chain. The calculations taken into account the percentage of turnover for each relevant sector attributed to small, medium and large companies to derive the average weighted per site by role figures used in these calculations.

42 EUROSTAT defines the GOS rate (i.e. % of turnover) as an indicator of profits. GOS equals gross output (turnover or gross premiums in Eurostat)) less the cost of intermediate goods and services to give gross value added, and less compensation of employees and taxes and subsidies on production and imports. It is gross because it makes no allowance for consumption of fixed capital (CFC).

Table 4-4: Percentage of production costs attributed to electroplating – counts of respondents						
	< 5%	6% - 30%	31% - 50%	51% - 75%	>75%	No response
Build-to-Print	1	7	0	2	4	1
Design-to-Build	4	2	1	1	2	2
OEMs	1	1	0	0	0	2
*These responses cover multiple sites						

Results from the SEA questionnaire suggest that for most companies electroplating accounts for under 30% of their total aerospace and defence production costs. However, for 30% of companies, electroplating accounts for over 50% of their aerospace and defence related production costs.

Given the importance of electroplated components and final products to A&D, there is no direct linkage between the share of production costs and revenues; the loss of electroplating would have a far greater impact on revenues and the financial viability of the companies involved than suggested by its share production costs. For most companies, electroplating accounts for more than 75% of their total revenue, as shown in **Table 4-5**.

Table 4-5: Revenues generated by chromate using processes						
	<10%	10% - 25%	25% - 50%	50% - 75%	>75%	No response
Build-to-Print	1	1	1	2	10	0
Design-to-Build	0	0	0	1	11	0
OEMs*	1	0	0	1	2	3
*These responses cover multiple sites						

Most BtP companies undertake electroplating activities only for the aerospace sector, whereas DtB to design companies primarily (62%) undertake activities for other sectors. These other sectors include machinery, medical equipment and automotive.

4.2.3.4 Investment in R&D, risk management measures and monitoring

OEMs

OEMs have invested into research and development of their electroplating processes, with budgets allocated for research and development into chromate substitution ranging from €250,000 to €7 million across the different companies. These budgets are on the increase, demonstrating the importance of substitution for OEMs.

Investments have also been made into both improving the existing CT based process (improvements in the efficiency and reductions in emissions). Across the companies, since 2017, between €120,000 and €8 million has been spent upgrading their existing electroplating processes. With regard to installation of chrome-free technologies, one of the OEMs has implemented Cr(III) plating lines at a number of its sites, at a cost of around €3.5 million.

Further information on research and development by OEMs is covered in Section 3.4 including R&D collaborations such as HITEA and HardAlt.

Design-to-Build suppliers

Design-to-Build companies have also invested in improving their electroplating processes, including installation of new baths and lines. These investments have been made as recently as 2019, with costs varying between €20,000 and €2.5 million. The investments are expected to have a lifetime of 10 to 25 years.

Five of these companies also operate chromate-free plating lines. Some report undertaking research starting in 2015 but still not having gained certifications for use of alternatives on their products, while others have been able to gain certifications or their customers have gained certifications for use of alternatives on the types of components they supply. Examples of alternatives which have been invested in include the use of black electroless nickel electroplating at a cost of €45,000 (investment in 2021 following certification of components using this alternative with an expected lifetime of 15-25 years), and Cr(III) technology including investments varying between €10,000 and €160,000.

Build-to-Print suppliers

Investments have been made as early as 2007 into improvements in the electroplating processes being used by respondents to the questionnaire. This includes new process lines and new tanks. Investments varied between €4,000 and €1 million with lifetimes from eight to 25 years. As a result, in total, five BtP companies now operate plating lines that are chromate free as well as having lines for components that require the use of chromium trioxide.

It should also be noted that some of these suppliers will have to be National Aerospace and Defence Contractors Accreditation Program (NADCAP) accredited and will be subject to International Standards Organisation (ISO) audits of their processes using the chromium trioxide, in order to secure and hold accreditations/certifications required by their customers (in other cases, the OEM will qualify/certify their suppliers rather than require NADCAP accreditation). This expenditure varies by company size, with related costs quoted as varying from e.g. €10,000 to €60,000 to €200,000 per company.

MROs

In terms of development of the chromate using process, MROs have also invested in new tanks and in renovating electroplating shops. Additionally, the MROs have invested in emissions monitoring equipment. The costs of such investments by one MRO are estimated at €4,000,000. At present, none of the MROs operate chromate-free electroplating processes, as none are currently allowed under the requirements set out in the Maintenance Manuals which they must adhere to.

Two of the MROs have been working with the OEMs on R&D into alternatives. One has spent around €500,000 on such R&D, with these costs attributed to:

- Test pieces/specimens
- Chemical products and bath analyses
- Tanks and tank equipment
- Laboratory equipment, and
- Characterizations of the treated components/specimens.

4.2.3.5 Potential benefits from on-going substitution under the Continued Use Scenario

In addition to collecting information on economic characteristics, companies were also asked whether they expected there to also be potential benefits (under the continued use scenario) in the future with a move to alternatives once these had been certified and implemented. A range of potential types of benefits were identified in the SEA questionnaire, with companies asked to identify those that they thought might arise as progression is made in the substitution of chromium trioxide.

Across respondents, regardless of role in the supply chain, most companies identified better relations with authorities as a benefit. A few also identified better public, shareholder and community relations, with this identified particularly important to the OEMs.

4.2.4 End markets in civil aviation and defence

4.2.4.1 Importance to end markets

The use of chromate-based electroplating provides extremely important wear and corrosion resistance and other beneficial properties to civil aviation and other aerospace and defence products that must operate safely and reliably, across different geographies, often in extreme temperatures and precipitation, and in aggressive environments with environmental and service temperatures ranging from below minus 55°C at cruising altitude to in excess of plus 200°C, wide ranging and varying humidity and pressure, high and varying loads and varying modes of stress. These components have high utilisation rates (around 16 hours a day for commercial, whilst critical defence systems must operate continuously for extended periods).

Because the use of chromium trioxide in electroplating cannot be fully substituted at present, it plays a critical role in ensuring the reliability and safety of final products. Thus, although the economic importance of chromium trioxide in electroplating is indirect in nature, its significance is clear with respect to:

- The ability of MRO companies to undertake their activities within the EEA and UK with this including the ability to carry out repairs with short turn-around times;
- The importance of timely MRO services to airlines, given the costs associated with aircraft being grounded and out of service for longer periods of time;
- The impacts that increased groundings of aircraft (Aircraft on the Ground - AoG) would have on the availability and costs of flights for passengers and for cargo transport, with reductions in passenger km and cargo km translating into significant economic losses not just within the EEA and UK but globally; and
- The importance of timely MRO services for military forces, given the critical importance of mission readiness and the avoidance of impaired operations, which could only otherwise be guaranteed by the purchase of additional aircraft and weapon systems to compensate for AoG or systems out of service.

The economic importance of ensuring that aircraft retain their airworthiness is illustrated by the figures quoted in Section 2 above for the number of air passengers transported in the European Union in 2019 (over 1 billion), as well as the net profits of the airlines in 2019 at US$ 6.5 billion (€5.8 billion, £5.1 billion).

The military importance of ensuring that military aircraft and equipment maintain their fleets and mission readiness cannot be quantified in the same manner; however, the involvement of four MoDs (as well as the MROs supporting military forces) in this Review Report through the provision of information demonstrates the critical nature of chromate-based electroplating to the on-going preparedness of their military forces.

4.2.5 Expected growth in the EEA and UK A&D sector

4.2.5.1 Civilian aircraft

Demand for new civilian aircraft is expected to grow into the future, as illustrated in **Figure 4–2**. Projected global compound annual growth rates (CAGR) for different aircraft classes for the period 2020-2031 are given in the figure below[43], with this suggesting a CAGR from 2020 to 2031 of around 2.5%.

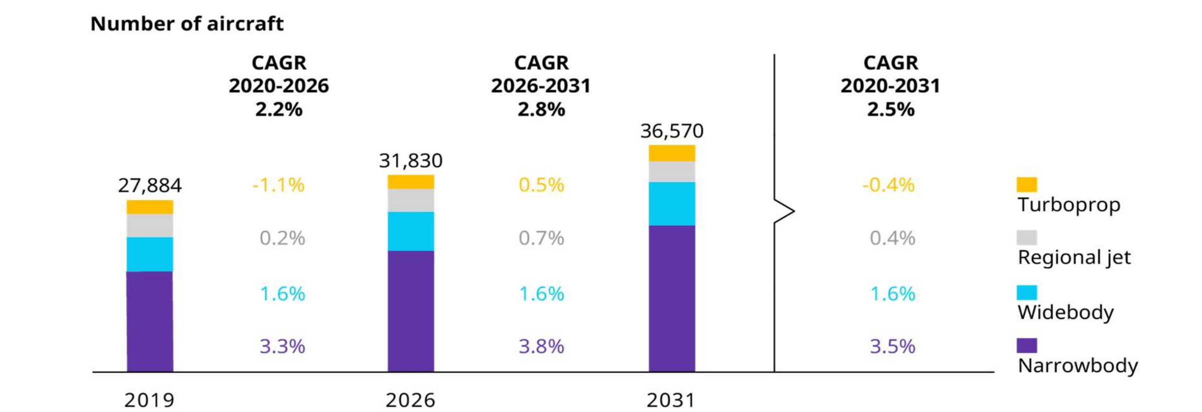

Figure 4–2: Global fleet forecast by aircraft class, 2020-2031
***Source:* Oliver Wyman analysis 2021[21]**

Market reports issued by Airbus and Boeing indicate that future growth is expected to extend beyond 2031. Airbus' Global Market Forecast for 2022-2041 predicts that passenger air traffic will grow at 3.6% CAGR and freight traffic will grow at 3.2% CAGR globally. By 2041, there will be some 46,900 aircraft in service, with this including an estimated 39,500 new passenger and freighter aircraft (and the retirement of some of the older aircraft. This includes delivery of new aircraft for the European market, as well as the Asian and Chinese markets.[44]

43 Oliver Wyman Analysis (2021): https://www.oliverwyman.com/our-expertise/insights/2021/jan/global-fleet-and-mro-market-forecast-2021-2031.html

44 https://www.airbus.com/sites/g/files/jlcbta136/files/2022-07/GMF-Presentation-2022-2041.pdf

Boeing's 2022 Commercial Market Outlook[45] indicates a similar level of increase, noting that the global fleet will increase by around 80% through to 2041 with the forecast value of new airplane deliveries at around US $7.2 trillion (based on a slightly higher growth in traffic at around 3.8% CAGR).

Based on figures publicly available on Airbus' website, the demand for new aircraft will progressively shift from fleet growth to accelerated replacement of older, less fuel-efficient aircraft. This will mean a need for over 39,000 new passenger and freighter aircraft, delivered over the next 20 years - around 15,250 of these will be for replacement of older less fuel-efficient models. By 2040, the vast majority of commercial aircraft in operation will be of the latest generation. Projections based on generic neutral seating categories (100+ seater passenger aircraft and 10 tonnes + freighters) are given in **Table 4-6** below.

Table 4-6: Airbus Global Market Forecast: projected new deliveries 2021-2040

Category	Africa	Asia-Pacific	CIS	Europe	Latin America	Middle East	North America	Total
Pax Units								
Small	860	13,660	1,160	5,220	2,170	1,570	5,050	**29,690**
Medium	140	2,350	120	1,040	180	420	640	**4,890**
Large	80	1,380	80	600	100	980	340	**3,560**
Total	**1,080**	**17,390**	**1,360**	**6,860**	**2,450**	**2,970**	**6,030**	**38,140**
Freight Units								
Small	-	-	-	-	-	-	-	**-**
Medium	10	120	40	40	10	20	210	**450**
Large	10	110	40	60	-	30	180	**430**
Total	**20**	**230**	**80**	**100**	**10**	**50**	**390**	**880**
Total Units								
Small	860	13,660	1,160	5,220	2,170	1,570	5,050	**29,690**
Medium	150	2,470	160	1,080	190	440	850	**5,340**
Large	90	1,490	120	660	100	1,010	520	**3,990**
Total	**1,100**	**17,620**	**1,440**	**6,960**	**2,460**	**3,020**	**6,420**	**39,020**

Source: Ascend, Airbus (undated): Global Market Forecast 2021 – 2040. Available at: https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast

When considering these figures, it is important to recognise that the European aerospace sector is a global exporter of aircraft, and A&D products make a significant contribution to the overall balance of trade. For example, France and Germany alone had export markets totalling over US$57 billion in 2020, while the UK export market was around US$13.2 billion in 2020.[46]

However, unless operations in the EEA and UK can remain financially viable in the short to medium term, the ability of EEA/UK based OEMs to carry out manufacturing at the levels implied by these compound annual growth rates is unlikely to be feasible. As a result, manufacture of these newer generations of aircraft and military products may shift to locations outside the EEA/UK with a consequent loss in Gross Value Added (GVA) to the EEA and UK economies, with enormous impacts on employment. This is despite the move to newer generation aircraft which could reduce future reliance on the chromate-based electroplating.

[45] https://www.boeing.com/commercial/market/commercial-market-outlook/index.page

[46] https://www.statista.com/statistics/263290/aerospace-industry-revenue-breakdown/

4.2.5.2 The MRO market

Not only would the manufacture of new aircraft in the EEA and UK be impacted but anticipated growth in the aftermarket components segment would also be affected. The aircraft spare components/final product market encompasses the market for both new and used rotable[47] components available as spares for aircraft and other products. This market was projected to grow with a CAGR of over 4% over the period from 2022-2027, although this rate may now be lower due to Covid-19. Growth is due to the increase in the commercial aircraft fleet as well as the need for timely MRO services to keep aircraft in service.

The MRO market was significantly affected by COVID-19 in 2020 but saw a gradual increase in demand as travel restrictions were lifted in 2021 and is expected to see positive growth over the next five to 10 years. Globally, the market is expected to have a CAGR of over 3% over the period from 2022-2027, as illustrated in the figure below.[48, 49]

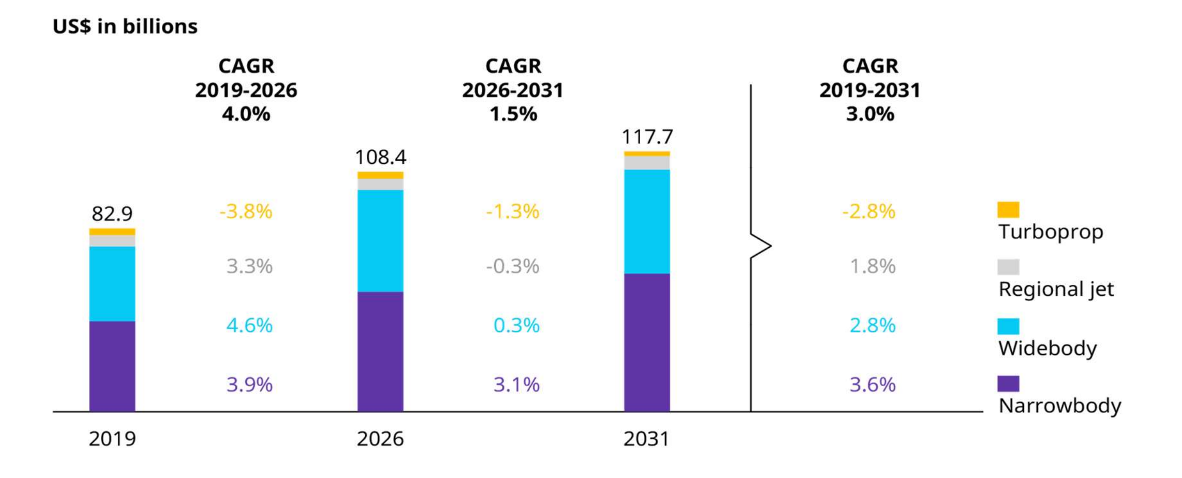

Figure 4–3: MRO market forecast by aircraft class, 2019-2031
Source: Oliver Wyman analysis

This growth is due to three factors: 1) Airlines are risk averse and try to maintain their fleets in an optimum condition, so as to delay the need to procure new aircraft, owing to the high investment costs of such aircraft. With COVID-19 severely impacting revenues and profit margins, more airlines are expected to resort to MROs to maintain fleet efficiency; 2) Airlines face very stringent MRO requirements so are not able to postpone MRO requirements; and 3) Increases in fleet sizes over the next five years will also lead to a continued growth in demand for maintenance and repair activities.

47 A component which is removed and replaced at pre-determined intervals measured in elapsed flight hours and/or flight cycles after which the removed item is sent for overhaul and will be subsequently re-used.

48 Mordor Intelligence, Commercial Aircraft Maintenance, Repair, and Overhaul (MRO) Market – Growth, Trends, Covid-19 Impact and Forecasts (2022 - 2027)

49 Oliver Wyman analysis: at: A forecast update on the global commercial airline fleet and aftermarket for 2020

4.2.5.3 The defence market

The war in Ukraine has led to several EEA countries and the UK to revisit their defence expenditure. Several countries that are NATO members and which previously did not meet the target of spending 2% of GDP on defence are now committed to meeting that target. This compares to Eurostat figures for total general government expenditure on defence in 2020 of around 1.3% of GDP for the EU[50]. The increase in investment will equate to hundreds of billions of Euros (e.g. Germany alone has pledged €100 billion in defence spending). Similarly, defence spending in the UK is expected to increase to over 2%, with projections in June 2022 suggesting 2.3% of GDP but Government commitments announced in October 2022 aiming for a target of 3% of GDP by 2030[51]. This equates to an increase in spending of around £157 billion between 2022 and 2030.

Such investment, which will include new spending on existing technologies, may also result in a continued reliance on the use of chromium trioxide for electroplating in the short to medium term until alternatives are certified for use in the manufacture of the relevant components and final products.

With respect to currently in-service products, the global military aviation maintenance, repair, and overhaul market registered a value of US $38 billion (€32 billion, £28 billion) in 2021, and it is expected to register a compound annual growth rate (CAGR) of over 2.5% during the forecast period 2022-2031. The European segment of this market is the fastest growing segment. The global civilian aircraft MRO market has a market size of US $70 billion (€59 billion, £51 billion) in 2021 and is growing even faster at a CAGR of over 4.6%.[52]

4.3 Annual tonnages of chromium trioxide used in electroplating

4.3.1 Consultation for the CSR

As part of preparation of the CSR, site discussions were held with ADCR members and some of their key suppliers. This work included collection of data on the tonnages of chromium trioxide used per site. The tonnages estimated equate to: up to 20,800 kg Cr(VI)/year per site, based on 300kg up to a maximum of 40,000 kg chromium trioxide used per site per year.

4.3.2 Consultation for the SEA

It is estimated that the average consumption of chromium trioxide in electroplating is 500 tonnes per annum in the EEA and 100 tonnes in the UK based on the consumption per site identified from the CSR; it is of note that the Article 66 notifications made to ECHA indicate that actual volumes are lower than these maximum figures.

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50 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Government_expenditure_on_defence

51 https://www.bloomberg.com/news/articles/2022-09-25/defence-spending-to-increase-by-at-least-52bn-in-response-to-russian-aggression or https://rusi.org/explore-our-research/publications/occasional-papers/famine-feast-implications-3-uk-defence-budget

52 https://www.prnewswire.com/news-releases/at-4-61-cagr-aircraft-mro-market-is-expected-to-reach-usd-97-12-billion-to-2028---exclusive-report-by-brandessence-market-research-301500861.html

4.3.2.1 OEMs

With respect to COVID-19, 61% of OEMs were impacted, with some sites experiencing as much as a 90% decrease in usage of CT over the two-year period. This is demonstrated by their substitution plans, which are further substantiated by responses to the SEA questionnaire.

OEMS are gradually reducing requirements for the use of chromate-based electroplating in their own production activities, as well as by their supply chains where they are design owners and they have been able to certify alternatives. However, until alternatives that meet customers' performance requirements and strict airworthiness requirements have been qualified, certified and then deployed across all components and products, use will continue; this includes in the production and delivery of new aircraft and other products. In addition, although COVID-19 led to some impacts on usage in 2020 due to the reduction in demand / cancellation of aircraft deliveries, no significant changes in usage compared to 2019 levels are foreseen up to 2024.

More generally, however, use of CT has remained steady over the last seven years at 39% of sites, with 17% of sites indicating that use has decreased by as much as 75%. Only 5% of OEM sites have increased their use of CT.

Use of CT in electroplating is likely to remain at similar levels up to 2024, and to then start decreasing up to 2028 with many OEM sites expecting usage to continue decreasing until 2032; some indicate that they expect to cease use of CT in electroplating by 2030, or 2032 at the latest (allowing for setbacks and implementation throughout their supply chain). Based upon the substitution plan, by 2035, 61% of companies expected to have reached TRL 9. As these companies do not account for the total volumes of the chromium trioxide used in electroplating, it is not possible to give an overall percentage reduction in volumes consumed on a year-by-year basis across the market.

4.3.2.2 Design-to-Build suppliers

With respect to COVID, 58% of design responsible suppliers providing responses to the SEA questionnaire stated that they had been impacted with impacts ranging from a 10% decrease to a 40% decrease in usage.

By 2024, 38% of companies suggested that they anticipated an increase in chromate usage of up to 20%. A further 38% suggested that there would be no change in usage. By 2030, 23% of companies expected decreased usage of 20% to 60%, however indicated that they expected reduced turnover as a result of this.

All respondents stated that they used chromium trioxide as a result of OEM requirements or as part of OEM MRO requirements. A further six use chromium trioxide due to their own certified processes.

4.3.2.3 Build-to-Print suppliers

With respect to COVID, 69% of BtP suppliers indicated that they had been affected, with impacts ranging from a 6% to a 50% decrease in overall consumption of chromium trioxide (across all activities – chromate-based and non-chromate based). Of the remaining 30%, most (23%) stated that their use of CT had remained steady over the last seven years (2014 to end 2021), with the remainder indicating that it has increased due to new contracts being won prior to 2019.

By 2024, the companies are split in terms of the likely direction of the change in consumption of CT in the future. 38% of companies expect their consumption to increase (to pre-2020 levels or slightly above) in the absence of their customers' certifying alternatives, while 31% expect the volumes they consume to decrease. Increases are estimated at between 10% and 25% and decreases are estimated at between 5% and 20%.

It should be noted though that BtP suppliers will often have no knowledge of their customers R&D or substitution plans. As a result, one would expect that their consumption of chromium trioxide for electroplating will decrease at the same rate as for the OEMs and DtBs

4.3.2.4 MROs

With respect to COVID, 50% of MROs state that they were affected, with reductions in activity up to 30%. As the sector recovers from COVID-19, the MROs expect consumption of CT to increase marginally or to decrease as alternatives to CT in electroplating are certified and implemented.

All MROs indicated that they use chromium trioxide due to the requirements of OEMs, hence trends in usage will be based on the substitution activities of the OEMs and lag due to the need for such changes to be carried through to updated Maintenance Manuals.

4.3.3 Article 66 notifications data

Under Article 66 of REACH, downstream users covered by an authorisation up their supply chain must notify ECHA of their use. As of 31 December 2021, ECHA had received 557 notifications relating to the REACH Authorisations listed above covering 619 sites across the EU-27 (and Norway)[53].

A key difficulty in using the Article 66 data is that reporting is based on tonnage bands rather than actual tonnage information. It is therefore difficult to derive estimates of annual tonnages based on this information, especially as actual tonnages used at individual sites making notifications may be significantly lower than the upper limit for each of the tonnage bands.

However, over 50% of the notifications indicate a tonnage band of 1 - 10 tonnes/year with a further 30% indicating 0.1 – 1 tonne/year. By inspection, the vast majority of notifications with higher tonnage figures relate to other sectors notably automotive, hydraulics and general engineering.

These data are consistent with an associated consumption of chromium trioxide of up to 500 tonnes per annum as determined from the SEA responses.

4.3.4 Projected future use of chromium trioxide

The aerospace sector is actively working to phase out the use of chromium trioxide. As indicated by the substitution plan, however, it will take further time however to qualify, validate, certify and implement alternatives within the supply chain across all components and products for A&D industry. Individual companies are at different points along this path, although this also varies by specific aircraft/defence application and across different types of components/final products.

Responses to the SEA questionnaire by OEMs indicate a downward future trend in the use of chromium trioxide over the review period despite the increase in demand for new aircraft and defence final products (although these responses were also provided prior to the war in Ukraine). However, it is also clear that almost half of the respondents will require a further 12 years to finalise R&D,

[53] Similar data is not publicly available for the UK

development, testing, qualification, validation, certification and industrialisation of alternatives at an industrial level, where the latter also includes making changes to specifications, drawings and maintenance manuals. A key reason cited for requiring a 12-year period relates to complexity of what needs to be achieved. As noted by respondents:

- *"For technical hard chrome plating, there is currently no viable alternative available in which we have faith for trials for some of our more special components and products. For specific defence applications, we expect that we will need 10 years to even find a technical alternative. The testing of the weapon equipment will start only after that, and also the changing of drawings and the like. Therefore: >12 years."*

- *"A 12-year review period is desired to ensure that alternatives can be implemented; however, the alternative's implementation depends on the approval of the customer."*

- *"Products in the aviation industry are designed, manufactured and maintained for use phases of several decades. In terms of civil aircrafts, such a use phase typically comprises 30-40 years. Even if new products - placed on the market in the short -/ medium term - might succeed in dispensing with the use of CrO3/Cr (VI) containing products, products already placed on the market (or until the expiration of the current review periods), still need to be maintained and repaired by applying binding maintenance specifications (which the user is legally obliged to comply with)."*

It is important to note that this planned reduction in usage by the OEMs will also impact on their BtP and DtB suppliers, as well as MROs, given that OEM specifications are the key driver for all suppliers/MROs. All BtP respondents indicated that use of chromium trioxide was required by their customers' or due to OEMs' requirements for MRO activities, as they rely on their design owners' specifications. This is not surprising given their role in the A&D value chain, and their reliance on design owners certifying alternatives for use in the production of different components. Additionally, all DtB companies stated that they use chromium trioxide due to OEM requirements.

As indicated above, MROs had difficulty predicting whether or not they would be able to move away from the use of chromium trioxide by and after 2032. Some expected use to decrease as alternatives are implemented and components/final products are certified, others for use to increase, while the majority expected it to either remain steady or were uncertain.

It is clear though, that continued use of CT will be required for a further 12 years (and potentially longer for some military products) as substitution efforts progress and to allow sufficient time for implementation (including a contingency period for setbacks). In particular, MROs, who are dependent on design owners' certifying alternatives, will require the use of CT for electroplating for a full 12 years, given the time periods required by the design owners to finish certification activities.

However, there is the potential that for both MROs undertaking maintenance and overhaul activities, as well as for DtB and BtP companies producing spare components (including for military final products), use will continue beyond the 12 years and for up to 20 years due to the long lifetimes of A&D final products and the infeasibility of gaining new certifications for products that have been in service already for long periods of time.

Phase-out of the use of CT in electroplating will therefore be gradual under the Continued Use scenario, as alternatives are certified and then implemented throughout supply chains. As noted by some of the BtP companies, once their customers' have certified alternatives, they will also need time to implement them at their site(s), also recognising that different customers have different requirements and are at different points in the substitution process. The time needed by the BtPs will be driven by having to raise the necessary finance, source and install any new equipment, and become qualified against the new alternative and process changes by customers. The industrial implementation is usually scheduled to follow a stepwise approach to minimise the technical risks, and benefit from lessons learned. This implies that the replacement is not implemented simultaneously in all plants and at all suppliers.

4.4 Risks associated with continued use

4.4.1 Classifications and exposure scenarios

4.4.1.1 Human health classifications

Chromium trioxide was included into Annex XIV of Regulation (EC) No 1907/2006 due to its intrinsic properties (mutagenic, carcinogenic, toxic for reproduction; depending on the chromate).

Chromium trioxide is classified as a Carcinogen 1A and a Mutagen 1B under the CLP Regulation. The most important route of exposure and target organs are inhalation causing lung cancer and oral exposure causing intestinal cancer. The substance is also classified as a Skin and Respiratory Sensitiser 1 and is a Reproductive Toxicant 2.

The hazard evaluation follows recommendations given by RAC (ECHA, 2015)[54]:

- For assessing carcinogenic risk, exposure-risk relationships are used to calculate excess cancer risks.
- As mutagenicity is a mode of action expected to contribute to carcinogenicity, the mutagenic risk is included in the assessment of carcinogenic risk, and low risks for mutagenicity are expected for exposures associated with low carcinogenic risks.

4.4.1.2 Overview of exposure scenarios

Due to the different levels in the supply chain to which the individual companies may be associated, and the variation in the size of the sites, the conditions under which the use is carried out can be variable. The conditions of use cover small sites and repair shops with rare and infrequent applications up to large sites with high throughput, and thus, a low to high level of automation for specific activities. This variability was also observed in extensive consultation processes during the preparation of the CSR. **Table 4-7** lists all the exposure scenarios (ES) and contributing scenarios assessed in the CSR.

[54] ECHA Website: https://echa.europa.eu/documents/10162/21961120/rac_35_09_1_c_dnel_cr-vi-_en.pdf/8964d39c-d94e-4abc-8c8e-4e2866041fc6; assessed in March 2021

Table 4-7: Overview of exposure scenarios and their contributing scenarios		
ES number	**ES Title**	**Environmental release category (ERC)/ Process category (PROC)**
ES1-IW1	Electroplating – use at industrial site	
Environmental contributing scenario(s)		
ECS 1	Electroplating - use at industrial site not leading to inclusion (of Cr(VI) or the reaction products) into/onto article	ERC 6b
Worker contributing scenario(s)		
WCS 1	Line operators	PROC9, PROC 13, PROC 28
WCS 2	Storage area workers	PROC 5, PROC 8b, PROC 28
WCS 3	Laboratory technicians	PROC 15
WCS 4	Maintenance workers	PROC 28
WCS 5	Incidentally exposed workers	PROC 0
Exposure scenario for industrial end use at site: ES1-IW1		

All A&D sites that perform electroplating within the ADCR supply chains are specialised industrial sites active in the EEA or the UK. They have rigorous internal health, safety and environment (HSE) organisational plans. A mix of technical, organisational and personal-protection-based and organisational measures are in place to reduce workplace exposures. The sites adhere to best practices to reduce workplace exposures and environmental emissions to as low as technically and practically feasible and use automated processes to the maximum extent possible. The possibility for and the degree of automation can vary between different sites and depend, amongst other factors, on the size of the site and the frequency with which the use in question is carried out.

As reported in Section 5, due to the conditions placed on the continued use of chromium trioxide in surface treatments (including electroplating), additional risk management measures were implemented by A&D companies with this involving significant investment. A full summary of these conditions is provided in the CSR that accompanies this combined AoA/SEA.

4.4.2 Exposure and risk levels

The CSR provides details of the approach and assumptions underlying calculation of exposures and risks from the use of CT in electroplating. The calculated exposure levels and associated excess cancer risks are presented below (for further information on their derivation see the CSR).

4.4.2.1 Worker assessment

Excess lifetime cancer risks

The findings of the CSR with respect to worker exposures, are summarised in **Table 4-8**, which presents the excess lung cancer risks to workers involved in electroplating treatment related activities. The risks are calculated using a combination of measured inhalation data and modelling for different SEGs (Similar Exposure Groups). The SEGs include:

- WCS1: Line operators for electroplating are usually involved in numerous activities related to the electrolytic process. Most of their working time they spend in a hall where the electroplating tanks are located and where the immersion process takes place, either on activities with direct or indirect Cr(VI) exposure.

- WCS2: Storage area workers are responsible for ordering, storing, transporting, delivering, and managing the chemicals used at a site. A considerable part of their working time they spend on transport and handling of chemicals in closed containers, where no opportunity for Cr(VI) exposure exists.
- WCS3: Laboratory technicians may be involved in activities related to electroplating with potential for Cr(VI)-exposure, but these tasks only account for a small fraction of their time and most of their work is not related to electroplating.
- WCS4: Maintenance and/or cleaning workers may be involved in activities related to electroplating with potential for Cr(VI)-exposure, but these tasks constitute only a small fraction of their time and most of their work is not related to electroplating.
- WCS5: Incidentally exposed workers are defined as workers who spend a relevant part (10% or more) of their working time in the work area where the treatment baths for electroplating are located, but do not carry out tasks with direct Cr(VI) exposure potential themselves. These workers may incidentally be exposed from such activities due to inhalation background exposure in the work area. Their tasks are required to be performed in this work area, as they are essential activities related to either the electroplating process or to other processes necessary to be carried out in the same workplace

Table 4-8 sets out the excess lifetime cancer risk for workers involved in each of the above tasks. also indicates the number of workers on average that may be exposed per typical site, with this figure taken into account in estimating the total number of workers exposed across all 125 EEA sites and 25 UK sites that would continue to carry out electroplating.

Table 4-8: Allocation of personnel at applicants' sites and excess lung cancer risk

#	SEG	Average number of workers exposed per site	Excess lifetime lung cancer risk [1/ug/m^3]
WCS1	Line operators	6 per site	3.82E-03
WCS2	Storage area workers	3 per day	3.48E-04
WCS3	Laboratory technicians	0-4 per site.	NA
WCS4	Maintenance workers	3 per day	3.84E-04
WCS5	Incidentally exposued workers	6 per site	1.00E-03

Source: Information from CSR
Note: Excess lung cancer risk refers to 40 years of occupational exposure

4.4.2.2 Humans via the environment

Excess lifetime cancer risks

The assessment of risks for humans via the environment presented in the CSR has been carried out for the general population at the local level only. No regional assessment has been carried out as it can be assumed that Cr(VI) from any source will be reduced to Cr(III) in most environmental situations and therefore the effects of Cr(VI) as such are likely to be limited to the area around the source, as described in the EU Risk Assessment Report for chromates (see the CSR for further details). The approach to not perform a regional assessment for human Cr(VI) exposure via the environment as part of AfAs for chromate uses was also supported in compiled RAC and SEAC (Socio-economic Analysis Committee) opinions, as described for example in the *Opinion on an Application for Authorisation for Use of sodium dichromate for surface treatment of metals such as aluminium, steel, zinc, magnesium,* *titanium, alloys, composites and sealings of anodic films (ID 0043-02)*. This reference states that regional exposure of the general population is not considered relevant by RAC[55].

The assessment presented in the CSR is based on measured data for emission to air and wastewater. For this assessment combined exposure of humans via the inhalation (air) and the oral (uptake of water and fish) route is considered. The resulting 90th percentile risk estimates are presented in the table below.

Table 4-9: Excess lifetime cancer risk estimates for humans via the environment (general population, local assessment)					
	Inhalation		Oral		Combined
	Local Cr(VI) PEC in air [µg/m3]	Inhalation risk	Oral exposure [µg Cr(VI)/kg x d]	Oral risk	Combined risk
90th percentile	5.08E-03	1.47E-04	3.52E-04	2.81E-07	**1.48E-04**
90th percentile, sites >1000 kg Cr(VI)/a	7.28E-03	2.11E-04	2.84E-03	2.27E-06	**2.11E-04**
90th percentile, sites <1000 kg Cr(VI)/a	5.97E-04	1.73E-05	1.53E-04	1.23E-07	**1.73E-05**
a) RAC dose-response relationship based on excess lifetime lung cancer risk (ECHA, 2013): Exposure to 1 µg/m3 Cr(VI) relates to an excess risk of 2.9x10-2 for the general population, based on 70 years of exposure; 24h/day. b) RAC dose-response relationship based on excess cancer risk for tumours of the small intestine (ECHA, 2013): Exposure to 1 µg/kg bw/day Cr(VI) relates to an excess risk of 8x10-4 for the general population, based on 70 years of exposure; daily exposure.					

4.4.3 Populations at risk

4.4.3.1 Worker assessment

Numbers of workers exposed based on Article 66 data

The Article 66 data on numbers of staff – or workers – exposed to CT is summarised in **Table 4-10** below for those Authorisations relevant to the continued use in electroplating. No downstream users have notified using CT under REACH/18/9 despite the authorisation being relevant to electroplating.

No similar data are publicly available for the UK.

Table 4-10: Number of workers exposed - Article 66 Notifications data			
Substance	**Authorisation number(s)**	**Use**	**Staff Exposed**
Chromium trioxide	REACH/20/18/7 REACH/20/18/11	Electroplating	689

[55] RAC/SEAC "Opinion on an Application for Authorisation for Use of sodium dichromate for surface treatment of metals such as aluminium, steel, zinc, magnesium, titanium, alloys, composites and sealings of anodic films", consolidated version, 2016; https://echa.europa.eu/documents/10162/658d42f4-93ac-b472-c721-ad5f0c22823c

Number of workers based on SEA questionnaire data

Responses to the SEA questionnaire indicated that 1,479 workers (FTE) are involved in electroplating related activities across the 68 sites for which data were collected. This is broken down in by role in the supply chain and extrapolated to the total 125 EEA sites and 25 UK sites.

Table 4-11: Employees linked to chromate-based electroplating treatment activities across all 150 sites					
Number of workers 150 sites	Number of sites EEA	Number of sites UK	No of employees EEA	No of employees UK	Total
Number of workers 68 sites involved in electroplating					
Build-to-Print	13	3	101	103	204
Build to design	19	1	935	0	935
MRO only	4	2	116	62	178
ADCR Members	19	7	158	4	162
Total 68 sites	55	13	1,310	169	1,479
Average per site			**23.8**	**13**	**21.75**
Number of workers at 125 EEA sites and 25 UK sites involved in electroplating					
Build-to-Print	69	8	540	309	814
Build to design	22	4	1,154	0	1,094
MRO only	11	4	258	124	446
ADCR Members	22	8	185	5	189
Total 150 sites	**125**	**25**	**2,136**	**438**	**2,543**

In total, this works out at around 2,140 workers exposed at EEA sites and 440 in the UK, or between 13 and 24 per site, which is in line with data from the CSR suggesting between 16 and 22 per site. These figures will include workers across all relevant WCS.

The average figures given in the CSR are taken here, as they are based on site visits and detailed discussions with companies. The average figures assumed in the CSR extrapolated out to the total numbers of sites gives the figures set out in **Table 4-12** as the number of workers exposed under each WCS. Note that WCS3 related to laboratory technicians is not considered further as the handling of substances in laboratories for quality control purposes under controlled conditions and in amounts below 1 tonne per annum falls under the REACH Art. 56(3) exemption[56]. Furthermore, the sampling activities that may be carried out by lab technicians are covered under other WCS.

[56] https://echa.europa.eu/de/support/qas-support/browse/-/qa/70Qx/view/ids/585-1442-1443-1498-1565

Table 4-12: Number of employees undertaking electroplating across the EEA and UK				
Worker Contributing Scenarios		Average No. Exposed from CSR	EEA sites	UK sites
WCS1	Line operators	6	750	150
WCS2	Storage area workers	3	375	75
WCS3	Laboratory technicians	4	500	100
WCS4	Maintenance and/or cleaning workers	3	375	75
WCS5	Incidentally exposed workers	6	750	150
Total		22	2750	550

4.4.3.2 Humans via the Environment

The relevant local population for humans via the environment has been estimated based on the following information:

- Number of downstream user sites in total and then as assumed in terms of their distribution across the EEA/UK;
- The population density per km^2 for each relevant EEA country and the UK;
- The relevant distance from sites for the local assessment, taken as the default assumption of a 1000m radius (or 3.14 km^2).

A 1000m radius is adopted here to estimate the exposed population as, for most sites, the HvE results are driven by emissions to air. Oral exposure risks are typically much lower and for six of the electroplating sites no wastewater is released; in these cases, inhalation risks were lower than average. As a result, adopting the EUSES default assumption related to the capacity of local sewage treatment plants would over-estimate the number of inhabitants that may be exposed due to emissions from each site.

The resulting estimates of the number of people exposed within the general population are given in **Table 4-13** for the EEA and UK. The total number of humans exposed via the environment in the EEA is estimated at around 66,000, with the UK figure being around 33,300 (with the UK figure being disproportionately higher due to its population density). The distribution of sites is based on the percentages of Article 66 notifications made by sites in the different EEA countries specific to functional chrome plating.

As noted above, no assessment of risks for humans via the environment at the regional level has been carried out based on RAC's previous opinion that regional exposure of the general population is not relevant.

Table 4-13: General public, local assessment exposed population from electroplating across the EEA and UK			
Countries with DUs	**No. Sites per country**	**Population density per km²**	**Exposed local population within 1000m radius**
France	12	118	4448
Germany	36	232	26239
Italy	29	200	18221
Spain	10	92	2890
Poland	9	123	3478
Czech Republic	5	135	2121
Sweden	2	23	145
Finland	1	16	50
Netherlands	2	421	2645
Belgium	2	376	2362
Denmark	1	135	424
Hungary	2	105	660
Norway	1	14	44
Romania	1	82	258
Bulgaria	1	64	201
Ireland	1	69	217
Greece	2	82	515
Slovakia	1	111	349
Portugal	1	112	352
Slovenia	1	104	327
Malta	1	1633	5130
Austria	3	107	1008
Croatia	1	71	223
Total	**125**		**65,945**
UK	**25**	**424**	**33,301**

4.4.4 Residual health risks

4.4.4.1 Introduction

Under the Applied-for-Use Scenario, use of chromium trioxide in electroplating will continue up to the end of the current Review Period for a total of 12 years.

In December 2013, the Risk Assessment Committee (RAC) agreed lifetime (i.e. for 40 years and 70 years of exposure) mortality risk estimates associated with carcinogenicity for workers and humans via the environment exposed to Cr(VI) substances[57]. It assumes a linear relationship for both lung and intestinal cancer.

As the excess cancer risk estimates apply to each exposed worker for a total working life of 40 years, they need to be adjusted to reflect exposures over the length of the review period. Exposures are thus treated as separable over time, meaning that annual risk is equivalent to 1/40 of the risk over 40

[57] ECHA (2013): Application for authorisation: Establishing a reference dose response relationship for carcinogenicity of hexavalent chromium. Helsinki, 04 December 2013. RAC/27/2013/06 Rev. 1 (agreed at RAC-27).

years of exposure. For members of the general population, excess cancer risks estimates apply for a lifetime of 70 years, meaning that annual risk is equivalent to a 1/70 of the risk of 70 years of exposure.

4.4.4.2 Morbidity vs mortality

Excess cancer cases need to be split between fatal and nonfatal ones. To this end, estimates of fatality and survival rates associated with lung and colorectum[58] cancer cases were derived from the Cancer Today database, see **Table 4-14** below.

Table 4-14: Estimated incidence and mortality of cancers across the EU-27 and the UK, both males and females (in 2020)

Type of cancer	Cases	Deaths	Survivals
Lung	370,310	293,811 (79%)	76,499 (21%)
Colorectum (intestinal)	393,547	177,787 (45%)	215,760 (55%)

Source: Source: http://gco.iarc.fr/today/home (accessed on 20/02/2022)
Note: Percentages have been rounded

To calculate the number of additional non-fatal lung cancer cases, a ratio of deaths to survivals is applied to the number of additional fatal lung cancer cases, as shown below:

(1) $(0.21/0.79) \times \pi = \sigma$

where π is the number of additional fatal lung cancer cases and σ is the number of additional non-fatal lung cancer cases.

In a similar fashion, the figures from Cancer Today reported **Table 4-7** above are applied to the estimates to calculate the total number of additional fatal and non-fatal intestinal cancer cases[59] .

(2) $(0.55/0.45) \text{ x } \delta = \eta$

where, δ is the number of additional fatal intestinal cancer cases and η is the number of additional non-fatal intestinal cancer cases. Note, however, that the CSR provides combined excess risk estimates. To err on the side of conservatism, the fatality versus morbidity ratio for lung cancer has been adopted for valuation of risks to humans via the environment (HvE).

4.4.4.3 Predicted excess cancer cases with continued use: workers directly exposed

Total excess cancer risk cases are based on the excess lifetime risk estimates derived in the CSR for the different worker contributing scenarios (WCS as presented in **Table 4-9**). These risk estimates reflect the additional safety measures that have been implemented due to the conditions placed on continued use by the initial authorisations. The number of excess risk cases is calculated by multiplying the number of workers assumed to be exposed in each task by the value of the excess cancer risk given above adjusted for the requested review periods, i.e. over 12 years. This value is then multiplied by the number of workers exposed in each SEG to calculate the total excess cancer cases arising from

[58] Colorectum is taken as a proxy for intestinal cancer cases.

[59] It is assumed that here the dose response relationship pertains to both additional fatal and non-fatal intestinal cases.

the continued use of chromium trioxide in electroplating. The results are shown in **Table 4-15** for the EEA and **Table 4-16** for the UK.

Table 4-15: Number of excess lifetime cancer cases to EEA workers					
WCS	Number of persons exposed	LUNG CANCER - Excess lifetime cancer risk	Excess number of lifetime cancer cases	LUNG CANCER - Number of excess lifetime fatal cancer cases	LUNG CANCER - Number of excess lifetime non-fatal cancer cases
WCS1	750	3.82E-03	**2.87**	**2.26**	**0.60**
WCS2	375	3.48E-04	**0.13**	**0.10**	**0.03**
WCS4	375	3.84E-04	**0.14**	**0.11**	**0.03**
WCS5	750	1.00E-03	**0.75**	**0.59**	**0.16**
		Years - Lifetime	40.00	3.07	0.82
		Years - Review period	12.00	0.92	0.25
		Years - Annual	1.00	0.08	0.02

Table 4-16: Number of excess lifetime cancer cases to UK workers					
WCS	Number of persons exposed	LUNG CANCER - Excess lifetime cancer risk	Excess number of lifetime cancer cases	LUNG CANCER - Number of excess lifetime fatal cancer cases	LUNG CANCER - Number of excess lifetime non-fatal cancer cases
WCS1	150	3.82E-03	**0.57**	**0.45**	**0.12**
WCS2	75	3.48E-04	**0.03**	**0.02**	**0.01**
WCS4	75	3.84E-04	**0.03**	**0.02**	**0.01**
WCS5	150	1.00E-03	**0.15**	**0.12**	**0.03**
		Years - Lifetime	40.00	0.61	0.16
		Years - Review period	12.00	0.18	0.05
		Years - Annual	1.00	0.02	0.00

4.4.4.4 Predicted excess cancer cases with continued use: humans via the environment

The total number of people exposed as humans via the environment as given in **Table 4-13** is multiplied by the excess cancer risk estimates to calculate the total excess cancer cases arising under the continued use scenario. The results are given in **Table 4-17**. The basis for estimating the number of people exposed per country is the percentages of Article 66 notifications made to ECHA per country, as described in Section 4.2.

Table 4-17: Number of people in the general public exposed (local assessment) across the EEA and UK							
Countries with DUs	No. Sites per country	Population Density per km2	Exposed local population	Combined excess lifetime cancer risk	Excess number of lifetime cancer cases	Number of excess fatal cancer cases	Number of excess non-fatal cancer cases
France	12	118	4448	1.48E-04	6.58E-01	0.52	0.14
Germany	36	232	26239	1.48E-04	3.88E+00	3.07	0.82
Italy	29	200	18221	1.48E-04	2.70E+00	2.13	0.57
Spain	10	92	2890	1.48E-04	4.28E-01	0.34	0.09
Poland	9	123	3478	1.48E-04	5.15E-01	0.41	0.11
Czech Republic	5	135	2121	1.48E-04	3.14E-01	0.25	0.07
Sweden	2	23	145	1.48E-04	2.14E-02	0.02	0.00
Finland	1	16	50	1.48E-04	7.44E-03	0.01	0.00
Netherlands	2	421	2645	1.48E-04	3.91E-01	0.31	0.08
Belgium	2	376	2362	1.48E-04	3.50E-01	0.28	0.07
Denmark	1	135	424	1.48E-04	6.28E-02	0.05	0.01
Hungary	2	105	660	1.48E-04	9.76E-02	0.08	0.02
Norway	1	14	44	1.48E-04	6.51E-03	0.01	0.00
Romania	1	82	258	1.48E-04	3.81E-02	0.03	0.01
Bulgaria	1	64	201	1.48E-04	2.98E-02	0.02	0.01
Ireland	1	69	217	1.48E-04	3.21E-02	0.03	0.01
Greece	2	82	515	1.48E-04	7.63E-02	0.06	0.02
Slovakia	1	111	349	1.48E-04	5.16E-02	0.04	0.01
Portugal	1	112	352	1.48E-04	5.21E-02	0.04	0.01
Slovenia	1	104	327	1.48E-04	4.84E-02	0.04	0.01
Malta	1	1633	5130	1.48E-04	7.59E-01	0.60	0.16
Austria	3	107	1008	1.48E-04	1.49E-01	0.12	0.03
Croatia	1	71	223	1.48E-04	3.30E-02	0.03	0.01
Total	**125**		**65,945**	**1.48E-04**	**10.70**	**8.45**	**2.25**
			Years – Lifetime cases		**70.00**	**7.71E+00**	**1.65E+00**
			Years - Review period		**12.00**	**1.32E+00**	**3.51E-01**
			Years - Annual		**1.00**	**1.21E-01**	**3.21E-02**
UK	**25**	**424**	**33301**	**1.48E-04**	**4.93E+00**	**3.89**	**1.03**
			Years – Lifetime cases		**70.00**	**3.89E+00**	**1.03E+00**
			Years - Review period		**12.00**	**6.67E-01**	**1.77E-01**
			Years - Annual		**1.00**	**5.56E-02**	**1.48E-02**

4.4.5 Economic valuation of residual health risks

4.4.5.1 Economic cost estimates

In order to monetise human health impacts, a timeframe that goes from the end of 2024 to the end of 2036 (i.e. a 12-year review period) has been used and a 4% discount rate has been employed for calculating net present values[60]. It has been assumed that the levels of exposure to Cr(VI) for workers and members of the general population remains constant throughout the length of the review period, even though this is a very conservative assumption. In fact, downstream users will gradually reduce the amount of Cr(VI) consumed as the transition to the various alternatives proceeds. Combined with the investment in risk management measures put in place by the sites to protect workers as a result of the conditions placed on continued use by the initial authorisations, this should ensure that excess lifetime cancer risks reduce over the review period.

The economic valuation of the health impacts takes into account two important welfare components, the costs associated with mortality and morbidity. The basis of our calculations is the study led by the Charles University in Prague[61] and undertaken for ECHA.

That study was critically reviewed by ECHA in 2016 and the results of that review have been the basis of the economic valuation performed here[62]. The values used are:

- Value of statistical life for the avoidance of a death by cancer: €3.5 million (2012 prices); and
- Value of cancer morbidity: €0.41 million (2012 prices).

It is appropriate to update these two figures to 2021 prices (updated to second and third quarter values of 2021, more recent data are not available). This has been achieved by use of the Eurostat EU GDP deflator[63]. This suggests that the aforementioned figures should be multiplied by a factor of 1.12. Thus, the following values are employed in the analysis below:

- Value of statistical life (mortality): €3.5 million × 1.12 = €3.92 million (rounded); and
- Value of cancer morbidity: €0.41 million × 1.12 = €0.46 million (rounded).

In addition to these valuations, for the purpose of quantifying human health impacts, consideration has also been given to annual medical treatment costs for morbidity. A range of studies were identified that provide estimates of the costs of medical treatment for patients surviving lung and intestinal cancer. These are summarised in **Table 4-18**.

60 EC Better Regulation Toolbox – Tool #61: https://ec.europa.eu/info/sites/default/files/file_import/better-regulation-toolbox-61_en_0.pdf

61 Alberini, A. and Ščasný, M. (2014) Stated - preference study to examine the economic value of benefits of avoiding selected adverse human health outcomes due to exposure to chemicals in the European Union - Part III: Carcinogens.

62 ECHA (2016b) Valuing selected health impacts of chemicals. Available at: http://echa.europa.eu/contact

63 https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=teina110&plugin=1

Table 4-18: Alternative estimates of medical treatment costs			
Study	**Year for prices**	**Average direct costs in original units (per annum)**	**Direct costs in € 2019**
Lung cancer[64]			
Leal (2012)	2012	£9,071	€11,160
Braud et al (2003)	2001	€12,518	€15,800
Dedes et al (2004)	1999	€20,102	€23,460
Intestinal cancer (colon, colorectal and rectal cancer taken as proxies)[65]			
Luo et al (2010)	2000 (assumed)	US$29,196	€36,230
Lang et al (2009)	2006	US$28,626	€31,740
York Health Economics Consortium (2007)	2004	£8,808	€12,180
York Health Economics Consortium (2007)	2004	£12,037	€16,410

The average cost across the four lung cancer studies is €17,314 per annum (2021 prices). The average cost figures reported for intestinal cancer are based on figures produced for colon, rectal and colorectal cancer in the US and UK. The US figures are high compared to the UK data; as a result, the average across the two UK studies is taken here, with this being around €14,853 per case in 2021 prices, taking into account price inflation.

These average medical costs are annual figures and apply to survivors over the period of time that they continue to be treated. With respect to lung cancer morbidity cases, we have taken a percentage survival of 32% after one year since diagnosis, 10% after five years, 5% after 10 years. With respect to intestinal cancer morbidity cases, we have taken a percentage survival of 76% after one year since diagnosis, 59% after five years, 57% after ten years[66]. Based on these time periods, the NPV of average future medical costs per lung cancer case is estimated at €30,110 in 2021 prices, using a 4% future discount rate. The NPV of average future medical costs per intestinal cancer case is estimated at €82,620 in 2021 prices. It is noted that a large percentage of people survive intestinal cancer after a period of 10 years and any stream of health care costs incurred after that is not incorporated in our calculations. However, such costs are not likely to be relevant considering that those surviving after such a long period of time can either be considered as definitely cured or probably only in need of a small degree of medical attention.

64 Leal, J., 2012. Lung cancer UK price tag eclipses the cost of any other cancer, presentation by Health Economics Research Centre, University of Oxford to the NCIR Cancer Conference, Wednesday, 7 November. s.l.:s.n. Braud, L. & al, 2003. Direct treatment costs for patients with lung cancer from first recurrence to death in France. Pharmacoeconomics, 21(9), pp. 671-679. Dedes, K. J. & al, 2004. Management and costs of treating lung cancer patients in a university hospital. Pharmacoeconomics, 22(7), pp. 435-444.

65 Luo, Z. & al, 2010. Colon cancer treatment costs for Medicare and dually eligible beneficiaries. Health Care Finance Review, 31(1), pp. 33-50. Lang, K. & al, 2009. Lifetime and Treatment-Phase Costs Associated with Colorectal Cancer: Evidence from SEER-Medicare Data. Clinical Gastroenterology and Hepatology, Volume 7, pp. 198-204. York Health Economics Consortium, 2007. Bowel Cancer Services: Costs and Benefits, Final Report to the Department of Health, April 2007, York: University of York.

66 These values are based on a study conducted by Cancer Research UK on adults aged 15-99 in England and Wales from 2009-2013. https://www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/bowel-cancer/survival#heading-Zero

The valuations of mortality and morbidity were multiplied by the estimated number of additional cancer cases, fatal and non-fatal, that can occur in the Applied for use scenario. The basic calculations for the value of an excess cancer case are presented below:

(1) $(\pi \times (€\ 3{,}920{,}000)) + (\sigma \times (€\ 460{,}000 + €\ 30{,}840)$ = Total lung cancer costs

(2) $(\delta \times (€\ 3{,}920{,}000)) + (\eta \times (€\ 460{,}000 + €84{,}790))$ = Total intestinal cancer costs

4.4.5.2 Predicted value of excess cancer cases with continued use: workers

Table 4-19 applies the economic value of the associated health impacts to these additional statistical cases of cancer to generate the total economic damage costs of the excess lung cancer cases. Under the continued use scenario, the present value costs are **€1.3 million for the EEA and €269,000 for the UK**, based on the assumption that chromate-based electroplating continues at the current level of use over the entire review period; this will lead to an overestimate of the impacts as the sector transitions to the alternatives over the 12-year period.

Table 4-19: Present value and annualised economic value of mortality and morbidity effects to workers (discounted over 12 years @4% per year, 20 year lag, figures rounded)

	EEA Workers		UK Workers	
	Mortality	Morbidity	Mortality	Morbidity
Total number of lung cancer cases	9.22E-01	2.45E-01	1.84E-01	4.90E-02
Annual number of lung cancer cases	7.68E-02	2.04E-02	1.54E-02	4.08E-03
Present Value (PV, 2024)	€ 1,304,367	€ 40,688	€ 260,873	€ 8,138
Total PV costs	**€ 1,345,055**		**€ 269,011**	
Total annualised cost	**€ 310,518**		**€ 62,104**	
Source: Derived estimates from responses to the SEA questionnaire, Article 66 data, Eurostat data and CSR				

4.4.5.3 Predicted value of excess cancer cases with continued use: man via the environment

Table 4-20 applies the economic value of the associated health impacts to the additional statistical cases of cancer for the general population (humans via the environment) to generate the total economic damage costs of the excess cancer cases. Under the continued use scenario, the present value costs are roughly **€2.1 million for the EEA and €977 million for the UK**, based on the assumption that electroplating continues over the entire review period at 2024 tonnages; as indicated above, this reflects an overestimate of the levels of exposures as use declines with a transition to the alternatives over the 12-year period.

Table 4-20: Present value and annualised economic value of mortality and morbidity effects to the general population, local assessment (discounted over 12 years @4% per year, 20 year lag, figures rounded)				
	EEA General Population		UK General Population	
	Mortality	Morbidity	Mortality	Morbidity
Total number of cancer cases	1.32E+00	3.51E-01	6.67E-01	1.77E-01
Annual number of cancer cases	1.21E-01	3.21E-02	5.56E-02	1.48E-02
Present Value (PV, 2024)	€ 2,050,734	€ 69,865	€ 944,464	€ 32,176
Total PV costs	**€ 2,120,599**		**€ 976,640**	
Total annualised cost	**€ 489,560**		**€ 225,466**	
Source: Derived estimates from responses to the SEA questionnaire, Article 66 data, Eurostat data and CSR				

4.4.6 Human health impacts for workers at customers sites

Cr(VI) is reduced in this process to Cr(0) and no Cr(VI) is incorporated into or onto the surface layer. As a consequence, subsequent machining activities on treated components are not further included in this assessment.

4.4.7 Environmental impacts

In accordance with RAC's conclusions (see e.g., the RAC/SEAC "*Opinion on an Application for Authorisation for Use of sodium dichromate for surface treatment of metals such as aluminium, steel, zinc, magnesium, titanium, alloys, composites and sealings of anodic films*"[67]), no regional assessment has been carried out as it can be assumed that Cr(VI) from any source will be reduced to Cr(III) in most environmental situations and therefore the effects of Cr(VI) as such are likely to be limited to the area around the source, as described in the EU Risk Assessment Report for chromates (ECB, 2005). Therefore, combined exposures from various sources on the regional scale are not considered further.

4.4.8 Summary of human health impacts

Table 4-21 provides a summary of the economic value of the human health impacts across the worker and local populations. When considering these figures, it should be remembered that they relate to use of the chromium trioxide in electroplating activities across the sector at an estimated 125 EEA sites and 25 UK sites covered by this review report.

[67] RAC/SEAC, consolidated version, 2016; https://echa.europa.eu/documents/10162/658d42f4-93ac-b472-c721-ad5f0c22823c

Table 4-21: Combined assessment of health impacts to workers and general population value of mortality and morbidity effects to workers (discounted over 12 years @4% per year, 20 year lag, figures rounded)				
	EEA		**UK**	
	Mortality	**Morbidity**	**Mortality**	**Morbidity**
Total number of cancer cases	2.24E+00	5.96E-01	8.52E-01	2.26E-01
Annual number of cancer cases	1.98E-01	5.25E-02	7.10E-02	1.89E-02
Present Value (PV, 2024)	€ 3,355,101	€ 110,553	€ 1,205,337	€ 40,314
Total PV costs	**€ 3,465,654**		**€ 1,245,651**	
Total annualised cost	**€ 800,078**		**€ 287,570**	
Source: Derived estimates from responses to the SEA questionnaire, Article 66 data, Eurostat data and CSR				

5 Socio-Economic Impacts of the Non-Use Scenario

5.1 Non-use scenario

5.1.1 Summary of the consequences of non-use

The inability of companies to undertake electroplating across the EEA and the UK would be severe. This use is critical to providing wear resistance; corrosion resistance; hardness; coefficient of friction; layer thickness; and effect on surface morphology across a broad range of components and products. In particular, it is important to the protection of components such as landing gear and control components, weapon barrels, wheel axles and jet turbine engine components.

Additionally, the majority of suppliers of electroplating services are BtP suppliers, that tend to be SMEs and which may not be able to afford the investment costs to move over to an alternative or relocate outside the EEA and hence are more likely to cease operations in the non-use scenario.

If electroplating was no longer authorised and where qualified and certified alternatives are not available according to the definition of "generally available"[68]. Design owners (i.e. OEMs and DtB companies) would be forced to re-locate some or all of their components production, manufacturing and maintenance activities out of the EEA or UK, when qualified and certified alternatives are not available.

A refused Authorisation would have impacts on the EEA/UK formulators and the critical set of key functions provided by electroplating would be lost to A&D downstream users in the EEA and UK

⬇

Due to certification and airworthiness requirements, downstream users would be forced to undertake electroplating activities outside the EEA/UK or shift to suppliers outside of the EEA/UK

⬇

OEMs would shift manufacturing outside the EEA/UK as it would be too inefficient and costly to transport components for electroplating only

⬇

Design-to-Build suppliers may have more flexibility and are able to shift only part of their production activities outside the EEA/UK resulting in the loss of profits and jobs

⬇

Build-to-Print suppliers in the EEA/UK would be forced to cease electroplating and linked treatments, leading to closure or relocation and consequent impacts on profits and jobs

⬇

MROs would have to shift some of their activities outside the EEA/UK, where electroplating is an essential part of maintenance, repairs and overhaul activities

⬇

The relocation of MRO activities outside the EEA/UK would cause significant disruption to Aerospace and Defence

⬇

68 As defined with respect to the "legal and factual requirements of placing on the market" in the EC note of 27 May, 2020, available at: 5d0f551b-92b5-3157-8fdf-f2507cf071c1 (europa.eu)

Ministries of Defence would face logistical difficulties in maintaining aircraft and other equipment, severely impacting on mission readiness. Service agreements would need to be reached with non-EEA countries

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Civil aviation, passengers, freight shippers and emergency services would face reduced flight availability and routes, as well as increased costs

5.1.2 Identification of plausible non-use scenarios

Consultation was carried out with the applicants, OEMs, MROs and the BtP and DtB suppliers supporting them. These included discussions surrounding the most likely non-use scenarios taking into account not only the strict qualification and certification requirements placed on the aerospace sector but also how activities could otherwise be organised.

These discussions acted as the basis for a series of questions in the SEA questionnaire aimed at pulling out information on the role of different types of companies and how this impacts on why they use chromium trioxide, past investments and R&D, and the most likely impacts of a refused re-authorisation. The first three of these were discussed in Section 3 and the continued use scenario.

Moving to a poorer performing alternative was ruled out based on the unacceptability of such an option to the OEMs due to airworthiness requirements, as detailed further below. Producing components overseas, shipping them back to the EEA/UK and then warehousing them was ruled out due to logistic difficulties and economic feasibility.

Table 5-1 below presents the choices presented in the SEA questionnaire and a count of the number of companies selecting each (out of the 37 companies in total, covering 68 sites).

Respondents were asked to provide further comments to support their responses, and to explain any other possible responses not included in the above list. These comments demonstrate the differences that exist within the aerospace supply chain and hence how the most plausible scenarios will vary by role.

Further details on the non-use scenario for the different types of companies are provided below, starting with OEMs as the main design owners, followed by DtBs, BtPs and MROs.

Table 5-1: Responses to SEA survey on most likely non-use scenarios				
	OEM	Build-to-Print only	Design-to-Build only	MROs only
The decision is up to our customer		4	1	
We may have to cease all operations as the company will no longer be viable		7	5	4
We will focus on other aerospace uses or on non-aerospace and defence uses		1	2	
We will shift our work outside the EEA	5		1	
We will stop undertaking use of the chromate(s) until we have certified alternative	2	1	3	1
Other – e.g. move to a poorer performing alternative				
Number of responses (companies)	7	13	12	5

5.1.2.1 OEM

In discussions, the OEMs all stressed that the aim is the replacement of the use of chromium trioxide in electroplating to a qualified and certified alternative. In some cases, a candidate alternative has been identified, but more time is required for testing, qualification, validation and certification of the component using the alternative, prior to roll out across numerous suppliers.

With respect to the plausibility of the different non-use scenarios identified above, the following are clear from consultation based on the choices provided in the SEA questionnaire:

- **We will shift our work involving chromium trioxide to another Country outside the EEA.** This is the most plausible scenario for most OEMs and companies directly involved in the use of CT for electroplating. Given the reliance on the use of CT in electroplating in supply chains, it is also the most likely response for those OEMs who rely on suppliers carrying out electroplating on components prior to their delivery to the OEM. The reasoning behind this is detailed further below.

- **We will stop using chromium trioxide until we have certified alternatives:** In most cases substitution activities and especially the industrialisation phase of moving to alternatives will not be completed before the end of the current review periods, especially given the number of BtP suppliers and MROs involved, as well as the number of parts and components of relevance. In some cases, a significant number of additional years is required which would mean a potential stop to both production and associated MRO activities (as carried out by the OEMs, e.g. on turbines) over this period. The current “road map” for substitution and industrialisation cannot be speeded-up, and some margin is needed to allow for any delays or possible failures. The potential duration of such a production stoppage would not be economically feasible.

- We will focus on other aerospace uses or on non-aerospace and defence applications. The OEMs supporting the ADCR are mainly involved in the manufacture and repair of civilian and military aircraft. As a result, this scenario is not technically or economically feasible for most of them to switch all or most of their focus to other sectors, as their sole areas of expertise reside in the aerospace field and/or defence fields.

As a result, the OEMs indicated that if the viable alternatives are not qualified and implemented (or able to be implemented by the end of the current review period (i.e. September 2024) for chromium trioxide, then their **most plausible response under the non-use scenario would be to relocate all or some of their manufacturing activities outside of the EEA or UK** (it may also not be realistic given the efforts and expenditure involved in such relocation, which may be more likely to result in the complete closure of OEMs or divisions within them, with consequent impacts for the EEA/UK economies).

The extent to which the OEMs would move all or only some of their manufacturing outside the EEA/UK depends on the integrated "system" of activities undertaken at individual sites. Electroplating is critical to some of the OEMs and for the others to certain divisions. As noted in Section 2, the larger ADCR members may be supported by several suppliers and the non-authorisation of the continued use of CT for electroplating would have a significant impact on the ability of these suppliers to produce components for the OEMs. In terms of impacts on individual companies, the estimated loss of production and turnover ranges from around 30% to 100% of current levels at individual sites. As noted above, these impacts would be experienced by sites involved in civil aviation and/or defence manufacturing.

The impact of the decisions made by the OEMs (and to a lesser degree larger DtB companies) will determine the most likely responses across their supply chains. Due to the vertical integration of manufacturing activities, it is not feasible to only cease undertaking electroplating; all activities related to the manufacture of the relevant components and final products may need to be moved outside the EEA/UK. Note that this shifting of activity outside the EEA/UK may involve either relocation or sub-contracting (for smaller components although this would be accompanied by logistical issues including keeping inventories and dealing with repairs).

In the case of those companies producing components for defence final products, the option of relocation of production/surface treatment outside of the EEA could have political, economic and brand image implications: political (possible shift in the stability of international relationships), economic (price increase, loss of competitiveness, inability to fulfil past legal commitments – see also Section 5.1.2.5) and brand image (product not entirely manufactured in EEA). Moreover MoDs & Armed Forces, despite having good relationships with the OEMs as current suppliers, might be unwilling to buy a product partially produced in a country outside the EEA, especially if they are not part of the NATO Alliance.

Because aircraft manufacturing and MRO activities represent the largest share of the OEMs' activities, the impact on the European economy would be considerable, especially as their response would drive the responses of their suppliers.

In the A&D industry, reliance on proven wear and corrosion prevention processes means that Cr(VI) and non-Cr(VI) operations/processes normally exist side-by-side, are inter-reliant and non-separable; as a result, there is no possibility to identify and distinguish manufacturing plants as Cr(VI) or Cr(VI)-free. Indeed, the aerospace industry has a very complex and interrelated supply chain. Nonetheless, for many essential components, only one designated supplier exists. Typically, this supplier will have worked in close partnership with its customer(s) for decades to develop a product. Critical suppliers often take occupancy on, or adjacent to, the premises of their customers. Therefore, relocation will often be based on strategic decisions, e.g. if the customer relocates, the suppliers might do the same to keep proximity.

In conclusion, it is not possible to relocate the use of chromium trioxide based electroplating processes on their own in most cases. These processes are an integral part in the production chain and cannot be separated from previous or following process steps. As a result, the entire production chain would need to be relocated, which although the most plausible scenario is also not realistic and would lead to severe impacts on the viability of the entire value chain.

Particular difficulties would be faced by companies in the space and defence sectors. Possibilities for relocating some activities outside the EEA/UK are limited due to the difficulties related to achieving specific customer requirements, national security considerations, work share agreements, and financial restrictions. As a result, it is likely that there would need to be requests for "defence exemptions" so that those activities that contractually must be maintained in their current location could continue within the EEA/UK. It would also have implications for the manufacture of products for the European space industry, damaging its ability to remain independent.

5.1.2.2 Design-to-Build

Design-to-Build suppliers have a similar set of possible scenarios, including:

- Cease operations
- Focus on other aerospace activities or non-aerospace activities
- Stop using chromate based electroplating activities until components using an alternative are certified.
- Shift work outside of the EEA

A large proportion of DtB companies would have to cease operations. One company indicated that electroplating is the only process that it undertakes, and therefore continued operations would not be viable if the use of CT was not authorised. Others indicated that they would lose between 10% and 100% of turnover: six companies stated turnover losses of over 50%; and four stated turnover losses under 50%.

Most of the companies added that their business would not be economically viable due to the proportion of turnover attributed to electroplating. Those few that indicated that CT-based electroplating was not an important part of their turnover said they would therefore stop the process until they have found a qualified and certified alternative. At the same time, these companies also noted that the costs of development, qualification, certification and deployment of an alternative are high, which is an issue for some of the small to medium sized firms.

5.1.2.3 Build-to-Print

For Build-to-Print companies, the following are all potential scenarios:

- Cease operations;
- Focus on other aerospace activities or non-aerospace activities; and
- Stop carrying out chromate-based electroplating activities until components using an alternative are certified.

In practice, the potential responses of Build-to-Print companies to the non-use scenario are constrained. All confirmed that the choice of whether or not to use chromium trioxide is not theirs but their customers'. Three of the BtP companies already have operations outside of the EEA (in the UK, USA, Canada, India, China and Thailand), and two stated that their EEA based business would have to close in the event of a non-authorisation. Comments from respondents suggested that the processes would have to be subcontracted, including the disassembly and assembly processes and that this was unrealistic. The subsequent effects would include redundancies and losses in turnover for EEA operations, as well as the loss of NADCAP support.

Expected losses in turnover range from 30% up to 100%, over 50% of companies stated that they may have to cease operations, and therefore would have 100% turnover losses. Other companies (three of 13) were unsure of turnover losses due to reliance on the decision of their customers.

Significant investment, worker training and manufacturing documentation may be required to adapt the manufacturing processes for new alternatives, which sometimes require changes in existing facilities, the construction of new facilities, or switching to a different facility (including a different supplier's facility).

5.1.2.4 MROs

For companies that undertake a combination of BtP or DtB and MRO activities, the same options as identified above may apply to their non-MRO activities. For those that operate as MROs only, there is less choice. They will not undertake manufacturing per se, only the overhaul, repair, and maintenance of different aircraft components, which can differ in size and complexity (overhaul of a complete aircraft to maintenance of a single component).

When final products enter under the services of an MRO, the required maintenance effort, including which surface treatment processes may be required, is not directly foreseeable. Very often, the level of work required only becomes clear after disassembling the component. The surface treatment steps required (e.g. from pre-treatment to electroplating) for any given component is dependent on its condition and can differ for each maintenance event. As a result, not every component will pass through all potential surface treatment processes. Even where they do, levels of throughput are also dependent on the size and complexity of the component - processing times can range from five minutes to several days. Within these process flows, even if chromate-based treatments are required to a very limited extent, they remain essential.

For example, maintenance work may be performed at a customer's site on an assembled aircraft engine. This can involve non-destructive testing or component changes that do not require the complete disassembly of an engine. In the course of such maintenance work - depending on the findings – electroplating must be carried out on individual cases in order to complete the maintenance work to the prescribed extent and to be able to release the engine under airworthiness requirements. If this step is not possible, the entire maintenance process of the engine and thus the product is compromised.

The inability to use CT in electroplating as part of MRO activities as per the specification of the OEMs leaves maintenance, repair, and overhaul services unviable in the EEA. OEMs' service manuals are based on the qualified and approved uses of electroplating. Where required, MROs must use chromate-based electroplating as instructed.

As a result, MRO activities would have to cease in the EEA. One MRO states that they would cease activities until a certified alternative has been found. Due to the nature of MRO activities, this alternative would have to be tested and certified by OEMs before being added as a requirement to the service manual.

5.1.2.5 Additional considerations

Current industry best practice does not involve identifying manufacturing plants as Cr(VI) or Cr(VI)-free. To the contrary, in the A&D industry, reliance on proven wear resistant and corrosion prevention systems means that Cr(VI) and non-Cr(VI) operations/processes normally exist side-by-side, are inter-reliant and non-separable. The industry has a very complex and interrelated supply chain. Nonetheless, for several essential components, only one designated supplier exists. Typically, this supplier will have worked in close partnership with its customer(s) for decades to develop a product. Critical suppliers often take occupancy on, or adjacent to, the premises of their customers. Therefore, relocation will often be based on strategic decisions, e.g. if the customer relocates then the suppliers might do the same to keep proximity.

From an operational perspective, surface treatment using Cr(VI) substances is a small element of the overall process flow in most mixed facilities, with the combination of machining, finishing, assembly, testing and inspection dominating overall. However, as noted above, they cannot be separated from one another. The impacted operations, and therefore socio-economic impacts to industry under the non-use scenario, go far beyond the specific processes directly using Cr(VI) and have substantial implications for non-Cr(VI) processes that are indirectly affected.

Hypothetically, electroplated components could be produced outside of the EEA/UK and then be shipped back. However, this would drastically undermine the competitiveness of EEA/ UK component/assembly suppliers. By adding extra transportation, lead-times, and risk of additional handling-related damages, suppliers in the EEA /UK would be put at a massive disadvantage compared with non-EEA suppliers in their bids/services. Furthermore, if manufacturing activities using chromates versus chromate-free were separated on both sides of the EEA/UK borders, the logistic requirements of managing the flow of components/products and the level of transportation required would have dramatic impacts on resources and the environmental footprint of the sector.

5.1.3 Non-plausible scenarios ruled out of consideration

5.1.3.1 Move to a poorer performing alternative

Moving to a poorer performing alternative would not be acceptable to the OEMs, either from a Design Organisation Approval (DOA) perspective as approved by EASA[69], MoDs and the European Space Agency (ESA), or from an engineering perspective taking airworthiness safety requirements into consideration.

As noted in the parent applicants for authorisation, under the scenario of moving to a poorer performing alternative, OEMs would have to accept an alternative that is less efficacious in delivering wear resistance and corrosion protection where no alternative provides an equivalent level of performance to chromium trioxide. This use of a less efficacious alternative would downgrade the performance of the final product, and the reduction in the level of wear resistance and corrosion protection performance would give rise to several unacceptable risks/impacts:

- The highly likely risk of EASA (airworthiness authorities), MoDs or ESA not accepting a downgrade in performance;

[69] As defined by Commission Regulation (EU) 748/2012 which sets out the requirements that must be fulfilled by organisations that design aircraft, make changes to aircraft, repair aircraft and the parts and systems used in aircraft.

- Increased maintenance operations, leading to an increase in the downtime of aircraft and military equipment, increased costs of maintenance, less flying hours, etc.; and
- Increased risks to passengers, cargo operators and operators of military equipment.

Corrosion and wear issues likely would not appear suddenly, but after several years when hundreds of aerospace components are in-service. Further, potential decreased wear and corrosion protection performance from Cr(VI)-free coatings would necessitate shorter inspection intervals to prevent failures. Flight safety obligations preclude the aerospace industry from introducing inferior alternatives.

Additionally, as covered in Section 3, wear resistance (or any of the other key functionalities), cannot be considered in isolation. For example, achieving wear resistance should not impact the ability to treat complex geometries, or at least be comparable to the benchmark Cr(VI) solution. Any alternative is required to meet all of the key functionality currently provided by the chromium trioxide plating process for each affected component.

In the purely hypothetical case where decreased or loss of corrosion protection and wear resistance is introduced to aircraft, the following risk mitigation actions may be required:

- Substantial increase in inspections – both visual checks and non-destructive evaluations, such as ultra-sound crack tests, etc. Some inspections are very difficult or hazardous to perform (e.g. inside fuel tanks or inside fuselage/wing structures). All aircraft using less effective materials in repair/overhaul and/or unproven materials across the operating lifetime of an aircraft would be subject. A very conservative inspection frequency would be set to ensure safety until adequate in-service performance experience is obtained.
- Increased overhaul frequency or replacement of life-limited components. Possible early retirement of aircraft due to compromised integrity of non-replaceable structural components.
- An increase in the number of aircraft required by each airline would be needed to compensate for inspection/overhaul downtime and early retirement.
- Whole fleets may be grounded until a repair/replacement plan is in place for the whole aircraft fleet. This could impact many or all aircraft fleets.
- Defence systems would have similar impacts adversely affecting the continuity of national security.

Aerospace components are parts of major systems (fuselage; wings; engines etc.) and the hardware in these systems are designed to withstand similar criteria between overhauls. For example, a system is designed to achieve 25,000 cycles between overhauls and a new component is only rated for 5,000 cycles because of a Cr(VI)-free coating. By default, the entire system would now be de-rated to 5,000 cycles. Take a compressor blade that is located in the middle of an engine. If that blade can only survive for a portion of the life of an engine due to limitations of a new coating, the engine would require disassembly to access the blades. This means taking the engine off the wing, sending it to a repair centre, disassembling the engine and replacing the components at much shorter intervals than needed for the remainder of the engine, thus adding inherent inspection, maintenance, and repair costs to the manufacturers, operators, and end use customers, who will also be impacted by increased out of service times.

Because the lack of experience with Cr(VI)-free solutions can have a critical safety impact, the aerospace industry has a permanent learning loop of significant events and failure analysis and decisions for safety improvements. Part of this improvement is the introduction of the Maintenance

Steering Group 3 Analyse (MSG-3), specifically developed for corrosion. MSG-3 provides a system for Original Equipment Manufacturers (OEMs) and the regulators to identify the frequency of inspection with respect to the stress corrosion, protection and environmental ratings for any component or system.

Without adequate experience, proven success, and therefore possible unknown or hidden properties, the performance of a chromate-free system cannot be highly rated. Consequentially, a significant reduction to the maintenance interval is required, potentially cut in half. For cases with no long-term experiences or correlation to in-service behaviour, which is normally the case, a further reduction to the maintenance interval may be required. This would result in investment in additional spare A&D products to be used while products being repaired are out of service.

As a result, OEMs rule out moving to poorer performing alternative as a plausible scenario, as the risks are unacceptable. The primary objective of these companies is to move to an alternative. This objective cannot be achieved, however, without sufficient testing and flight (or other) data surrounding the use of alternatives. Without such data, the necessary approvals cannot be gained as the safety risk becomes too great, whether related to civil aviation or military aircraft. The corrosion resistance and wear resistance provided by electroplating is crucial to minimising any corrosion and wear related risks and hence to the manufacture of aircraft and other products in the EEA/UK; if there are no qualified alternatives then such manufacturing work would cease.

5.1.3.2 Overseas production followed by maintaining EEA/UK inventories

To be competitive, companies must keep inventory as low as possible ("just-in-time" delivery). Maintaining inventory clearly involves substantial costs (as elaborated below) and ties up cash. Stockpiling is also clearly not feasible for the repair and maintenance side of the business because the main aim of repair is to make components serviceable rather than replace them by spare components (which would run counter to the sectors drive towards increased sustainability).

The reasons why holding increased inventories is not a feasible option compared to maintaining and repairing damage include, but are not limited to, the following considerations:

- if no certified alternative is currently available or is likely to become available within months after the end of the Review Period, then there is no clarity on how long such an inventory must be available. For legacy aircraft, inventories will certainly be required for the next 20 years or more. Additionally, there is no visibility or clarity on customer demand in the short or longer term. Planned maintenance can be taken into account, but it is not possible to anticipate which components will be needed for unplanned maintenance and repair. Consequently, an assumption regarding the inventory that needs to be available for a sufficient duration would have to be made, leading to the risk of wasted resources or aircraft/equipment becoming obsolescent due to inadequate inventories.

- Stockpiling results in increased costs and would reduce the opportunity to invest in other projects/R&D, etc. The inventory costs would also have to be added to product costs and would therefore reduce competitiveness for operations in the EEA/UK.

- The costs of building adequate warehouse facilities in the EEA and the UK would be prohibitive and would not be economically feasible. In the UK, an industrial warehouse without climate control (which would be required for the storage of some A&D inventory) costs around €1000 per m^2 to construct (a conservative estimate). Its assumed here that warehouses that would act as a hub for storing inventory would be around 10,000 m2 as a minimum, given the range of components that would need to be stored. This implies a total build cost of around £10 million as a minimum, not taking into account the costs of land purchase, site preparation, design, construction, etc. which could easily add a further 25% even after taking into account any potential economies of scale in pricing due to the large size of the warehouse.[70] If such facilities are required at around 100 sites across the EEA and UK (to cover civilian and military requirements), then warehousing costs alone would lead to €1 billion in expenditure. These costs would be on top of the losses in profits that would occur from the need to subcontract manufacture to companies located outside the EEA/UK and the consequent profit losses and increased costs of shipping, etc.

- Facilities do not have enough production capacity to build up multi-year inventories, while also meeting current demand. Even if production capacities could be increased and adequate quantities of standard components be produced, there would be idle inventories for years beyond their need, which would in turn increase product costs for years. Importantly, the need to store this inventory under optimum conditions to avoid corrosion or damage over extended periods of stockpiling, would lead to further increases in costs.

- Existing facilities are not sized to store the amount of multi-year inventories required. Companies will need to build/invest in additional secure, high-quality warehouses to store the inventory.. Therefore, the entire aircraft would need to be transported to a non-EEA country for repair. If the plane is not airworthy, the effort and cost relating to transportation alone (e.g. from Belgium to Egypt) would be overwhelming.

- Even then, when existing inventories become depleted and no longer support necessary repairs and maintenance, increasing numbers of aircraft on ground (AOG) scenarios are inevitable, with associated costs. All transportable components would have to be sourced and produced from non-EEA suppliers sooner or later.

- Being dependent upon inventories and non-European suppliers (and in turn vulnerable to local economic and political issues affecting non-EEA countries or the UK), and thus unable to reliably fulfil MRO activities, will lead to inevitable delays and potential cancellation of flights, fines due to longer turn-around times and aircraft on ground scenarios.

- Companies make design modifications for single components as part of their normal course of business (for reasons other than chromate substitution). In these cases, all existing inventory would need to be written off for a loss. Furthermore, companies would not be able to produce the modified components in the EEA/UK anymore (if electroplating is still required). Consequently, it is clearly not possible to rely on a long-term stock of spare components that would fit all situations.

- It is impossible to hold a stock of all spare components at every airport. This would affect schedules, especially overnight stops as aircraft cannot be readily repaired and maintained. As a result, these aircraft would not be available for services next day and delays or flight cancellations would likely occur.

[70] See for example the cost model available at: https://costmodelling.com/building-costs

- Cost and environmental impacts of managing and disposing of waste components that could not be reused would be high. This seems to be inconsistent with the emphasis on waste reduction as a part of circular economy.

It is challenging to elaborate these quantitatively as they are multi-fold (i.e., increased cost of land and construction for warehousing, worker costs to secure and maintain inventory, increased delays and 'aircraft on the ground', writing-off stock) and there is no precedent to rely on, as this NUS is entirely contrary to current industry practice. However, it is immediately clear that the result would be that the cost of operating in the EEA/UK would increase considerably and the impact to society as a whole.

Furthermore, for certain types of components, increasing stock inventory is not feasible at all. In a very competitive industry, this would result in a migration of the entire industry (the inter-dependency of the industry is explained below and elsewhere in the SEA) to non-EEA/UK locations. As production moves outside the EEA/UK, related activities such as R&D will also re-focus to these countries. It can also be expected that future investment in associated industries and technologies will be most efficiently located alongside these activities.

5.1.4 Conclusion on the most likely non-use scenario

The most likely non-use scenario is driven by the responses of the OEMs to the non-use scenario. They are the customers that carry out the R&D and testing (sometimes in collaboration with their chemical suppliers and formulators) to determine whether an alternative is technically feasible, qualify and gain approvals for components using that alternative and then certify their suppliers against its use. In some cases, they also help their suppliers meet the financial costs of adapting existing facilities to enable them to move to the alternative.

As a result, the most plausible non-use scenario for the OEMs and suppliers drives the most likely non-use scenario for the sector as a whole. The most likely scenario is therefore the following:

1. EEA and UK suppliers of chromium trioxide would be impacted by the loss of sales, with the market relocating outside the EEA/UK. In the short term at least, i.e. 2 – 4 years, this would result in a loss of revenues and profits from sales in the EEA/UK. Over the longer term, some of the market may return to the EEA/UK but it is also likely that a significant proportion will have relocated more permanently.

2. OEMs and suppliers directly involved in electroplating surface treatments would move a significant proportion of their manufacturing operations outside the EEA/UK, with the consequent loss of significant levels of turnover and employment. In particular, they will be moving those manufacturing activities reliant on the use of electroplating where there is no qualified alternative or where implementation across suppliers after qualification and certification have been achieved is expected to require several years after the end of the current review period (e.g. 2-4 years after qualification). The losses to the EEA/UK would range from around 10% of manufacturing turnover for some sites to 100% of manufacturing turnover at others. **On average, it is assumed losses at affected sites would be around 70% of manufacturing turnover, with associated losses in jobs.**

   The above response is regardless of whether some warehousing is created in the EEA/UK, as this would only be relevant to smaller components.

3. OEMs who do not carry out electroplating themselves would still move some of their manufacturing operations outside the EEA/UK due to the desire to have certain treatment and production activities co-located within a region (i.e. to form clusters). This would facilitate the integration of manufacturing activities and associated maintenance and repair activities. As a result, there would be losses in turnover and employment associated with these companies also relocating.

4. As OEMs shift their own manufacturing activities outside the EEA/UK, they will have to carry out technical and industrial qualification of new suppliers or of EEA/UK suppliers moving to the new location, to ensure suppliers have the capability to deliver the stringent airworthiness and certification requirements. This would then be followed by a ramping up of production to meet manufacturing rate objectives. An alternative option would be increasing the capacities of existing non-EEA/UK electroplaters that are already qualified by OEMs.

5. In some cases, these newly located supply chains would be developed using DtB (and BtP) suppliers who have moved operations from the EEA/UK to other countries in order to continue supplying the OEMs. As the DtB companies undertake electroplating (and other surface treatments) for sectors other than aerospace and also using non-chromate based alternatives where these are certified, they are less likely to cease activities in the EEA/UK and hence as a group would be associated with a reduced level of profit losses. **For these companies, based on the SEA data and discussions with key design owners, it has been assumed that there would be a 40% loss of turnover.** It must be recognised that this level of turnover loss implies that some companies losing such a high percentage of turnover would still be able to cover their fixed costs and to remain financially viable.

6. However, a significant proportion of the existing BtP companies involved in electroplating will cease trading in the EEA as they do not also supply other sectors and are reliant on the aerospace sector; furthermore, the types of products that they manufacture are specific to the aerospace sector. This applies to those who indicated they "don't know" what the most plausible scenario would be for them and those that would cease trading or move outside the EEA/UK. There will also be significant loss of turnover for those that indicated they would cease electroplating only until a certified alternative was available or that they would shift to other activities. **Overall, the data indicate turnover losses across the BtP suppliers of around 70% for the affected companies in the EEA/UK.**

7. MROs will also be severely impacted and the larger operators indicated that they would move operations outside the EEA, due to the need to maintain vertical integration across the surface treatment processes that they are able to carry out. **The economic assessment assumes that 60% of turnover would be lost based on the responses of the larger MROs who services a large proportion of the civil aviation fleet.**

8. The re-location of MRO activities will have consequent impacts for civil aviation and military forces, as well as for the maintenance of defence products and aero-derivative products.

9. Airlines and their passengers would be impacted by increased costs and planes on the ground, while military forces' mission readiness would be impacted with the risk that equipment would also becoming obsolete and unavailable due to the inability to carry out repairs and/or maintenance activities according to manufacturer's requirements.

10. Taken together there would be significant economic impacts from the loss of manufacturing and maintenance to both the EEA and UK economies, together with the loss of highly skilled jobs (and potentially a highly skilled labour force) and the benefits derived from the R&D carried out by a high-tech sector.

The justification for this NUS takes into account the fact that OEMs and DtBs will not have components with certified alternatives which have been fully implemented across their supply chains by September 2024. Many will require a further 12 years to have fully implemented alternatives across all components/final products and EEA/UK supply chains. The regulatory requirements placed on the sector mean that unless components have certified alternatives there is no substitute which can be considered "generally available".

As noted previously, because of the complexity of the supply chain, and the close working partnerships that exist, a decision by an OEM or DtB to relocate will result in their suppliers relocating to keep proximity. Such relocation would involve not just the surface protection activities, but all activities due to the potential for corrosion or damage of unprotected surfaces during transport to another place. Using small amounts for Cr(VI) compounds for rework (or repairs) is mandatory and essential to the safety of the aircraft.

Moreover, the situation is the same even if a Cr(VI)-free alternative was successfully qualified for one or two components, but not all. Figure 5-1 illustrates the interdependency of every single component used, and the effect of only one component missing for the overall assembly process of the aircraft. It should be noted that this figure represents a highly simplified supply chain of components needed for the final assembly of an aircraft. If only one component cannot be produced according to type certification, the manufacture of the entire aircraft is jeopardised.

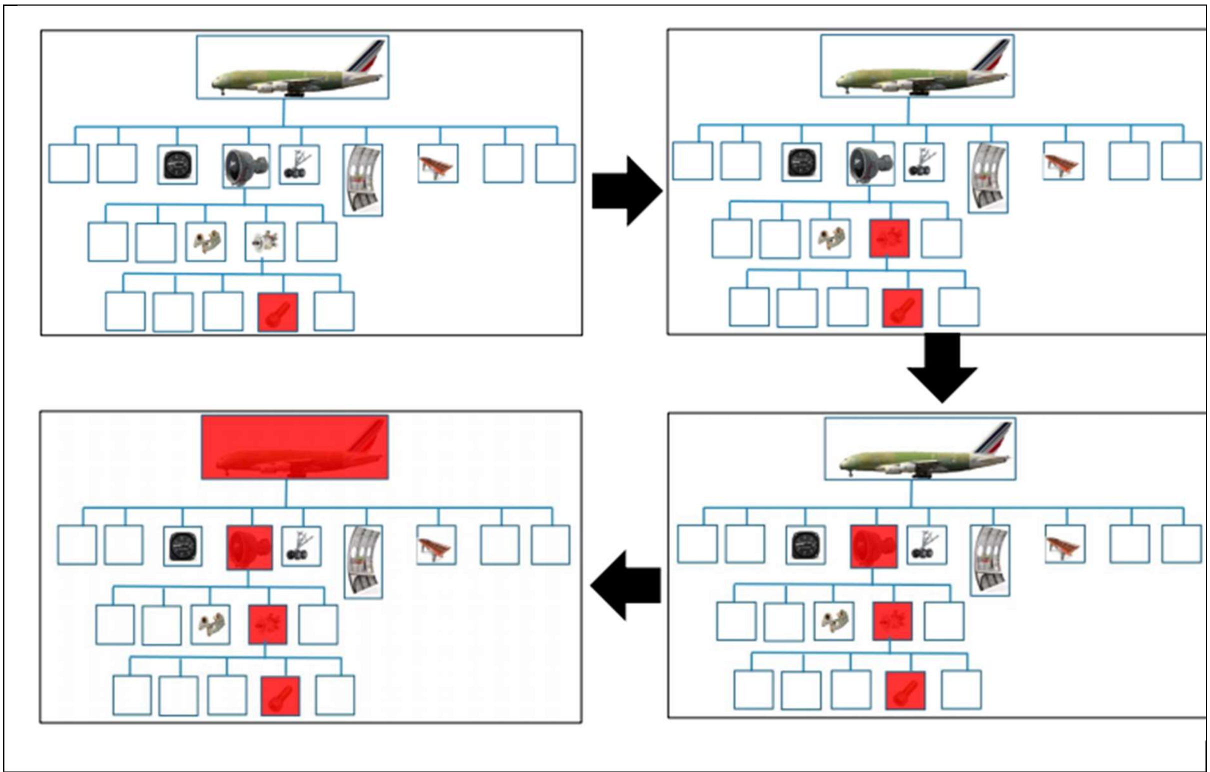

Figure 5–1: Interdependency of component availability in the manufacture of a final product

These arguments also hold for MRO activities, for example overhaul of turbine parts, which would be significantly affected under the non-use scenario. It is technically not possible (or economically feasible) to do the machining and repairs of a vane or other turbine component in the EEA or UK, then ship it to a non-EEA/UK facility for surface treatment, ship it back to the EEA/UK to further process the component, ship it back to a non-EEA facility for further surface treatment and ship and put it back in the turbine in the EEA/UK. Apart from the fact that the surface of the part could be damaged during transport, adding to the technical infeasibility of this situation, the very tight turnaround times and budgets are impossible to hold in such a scenario.

Given the above, under the NUS, the companies affected by the refused authorisation will move manufacture and repair of components and products out of Europe and the UK, together with jobs, know-how and R&D investments.

Finally, although this is considered the most plausible scenario, OEMs note that the obstacles that would have to be overcome in a short period of time may make it overly optimistic. The infrastructure of the sector is based in part around manufacturing clusters or hubs (see also **Figure 5-2**), with smaller suppliers located around the sites operated by the larger OEMs. Not all of these smaller sites, including those of critical suppliers, would be able to shift their activities outside the EEA/UK, leading to OEMs having to create entirely new supply chains outside the EEA/UK. This scenario also implies a huge economic investment would be carried out by the OEMs as well as their EEA/UK suppliers. This level of investment is unlikely to be feasible and in the meantime the OEMs would have to cease manufacturing activities in the EEA/UK until the new industrial facilities were in place and ready to operate outside the EEA/UK.

5.2 Economic impacts associated with non-use

5.2.1 Economic impacts on applicants

Under the non-use scenario, all applicants and the formulators of the electroplating products would be impacted by the loss of sales of CT or of imported formulations containing CT for use in electroplating.

In the short term (i.e. first 2 years under the non-use scenario), the losses will be in the order of Euro / Pound sterling tens of millions per annum to the applicants and their downstream formulators.

Over time, as consumption of CT reduces in line with companies' substitution plans, sales and hence revenues will continue to decrease. However, the formulators producing the chromate-based electroplating formulations are also the same companies that will be providing formulations based on the alternatives. As a result, sales of alternative formulations once they are certified and implemented across value chains would be expected to offset profit losses from declining demand for the chromate-based formulations.

No quantitative estimates for these losses are included in this SEA. These impacts are captured in the combined AoA/SEA for formulation.

5.2.2 Economic impacts on A&D companies

5.2.2.1 Introduction

It would be theoretically possible to move activities involving chromium trioxide use outside the EEA /UK due to already existing supply chain sites in other countries, for example, the USA, Canada, China, India, etc. and to outsource manufacturing as the supply chain is spread around the world. There are several obstacles to such a scenario, however, which would make this economically unattractive even if it is the most plausible scenario. Firstly, the due diligence principle will continue to apply to the supply chain and would be exacerbated in case of relocation out of EEA/UK. Secondly, when activities are shifted to another site, there is an inevitable phase of technical and industrial preparation (site design, capital procurement and installation, worker training, pilot trials) and qualification to ensure the sustainability of these activities including an assessment of the technical capability to deliver stringent airworthiness and certification requirements. Moreover, once the qualification phase is over, it is essential to get the right ramp up in order to meet the manufacturing rate objectives.

In the remaining time before the end of the initial review period, even if alternatives were qualified and certified across the manufacture of components and products, these two aspects are not realistic; it would require a huge economic investment that would significantly affect businesses with detrimental economic impacts. As a result, OEMs have indicated that they probably would be forced to stop manufacturing activities until the new industrial facilities and infrastructure are in place and ready to operate outside of the EEA/UK, with consequent impacts on the entire value chain. Given the current levels of civil aviation and anticipated growth, this would be catastrophic for aviation in the EEA/UK and globally.

5.2.2.2 Approach to assessing economic impacts

As noted in Section 1, the ADCR has been created as a sectoral consortium and downstream user members include competitors, which may also act as suppliers to each other; the larger companies also share many of the same BtP and DtB suppliers (an estimated 15-25% overlap in suppliers exists across some OEMs). These interlinkages have been taken into account in the estimation of economic impacts, which have been calculated for the OEMs, MROs and the associated BtP and DtB suppliers.

Two separate approaches have been used to estimate the magnitude of the potential economic impacts. Both are based on responses to the SEA questionnaire, with one taking as its starting point the number of jobs that would be lost while the other considers losses in turnover and what these imply in terms of losses in profits. Both approaches are used as a greater number of responses provided estimates of jobs lost than of the likely impacts on turnover (in percentage or actual terms).

1. **Estimates based on loss of jobs**: The first approach takes as its starting point the number of jobs that would be lost at the sites of SEA questionnaire respondents, based on their most likely response to the non-use scenario. This includes loss of jobs directly linked to use of chromium trioxide and losses in jobs at the site reliant upon the continuation of their use, i.e. jobs in related manufacturing and assembly activities. Importantly, it excludes losses in employment at local sub-contractors providing support services. The numbers of jobs lost are multiplied by the average Gross Value Added - GVA - per job (based on variations by role) to provide an estimate of total GVA lost. Personnel costs associated with this GVA are then subtracted to derive the implied losses in operating surpluses per annum.

2. **Estimates based on loss of turnover:** The second approach takes as its starting point the anticipated losses in terms of percentage of turnover reported by the respondents to the SEA questionnaire. Lost operating surplus is then calculated as an average per company based on role in the supply chain and Eurostat data on GOS as a percentage of turnover.

Both of these approaches provide proxy estimates of profit losses based on current levels of employment and turnover. They do not account for foregone future turnover under the continued use scenario due to the inability of the EEA/UK aerospace sector to respond to growth in the global demand for air traffic or to increased military and defence spending as a result of either a cessation in manufacturing activities or their relocating outside the EEA/UK.

The two approaches have been applied to account for uncertainty in the data available from the SEA questionnaire responses. Together they provide an interval, with one estimate acting as an upper bound and the other as a lower bound to the economic impacts.

5.2.2.3 Estimates based on loss of jobs (and GVA lost)

The SEA questionnaire collected data on the number of employees who would lose their jobs under the NUS which are directly linked to electroplating. Information was also sought on the number of jobs that could be affected due to a cessation of production activities or due to companies moving outside the EU.

For the purposes of this assessment, we focus on the numbers of jobs that would be lost should electroplating activities not be re-authorised, as well as losses stemming from the cessation of other linked surface treatment and manufacturing activities, including the manufacturing and assembly of aircraft and other military final products.

The job losses reported by respondents to the SEA questionnaire cover 55 sites in the EEA and 13 sites in the UK and have been extrapolated to provide estimates for the expected 125 EEA and 25 UK sites undertaking electroplating. The resulting estimates are presented in **Table 5-2**.

- For the 68 sites providing responses: Job losses by workers directly involved in CT-based electroplating and linked uses of the chromates would equate to 7,744, of which 5,915 would be in the EEA and 1,830 in the UK; and

- An additional 14,140 jobs (around 10,800 in the EEA and 3340 in the UK) would be lost by workers due to the cessation of linked assembly, manufacturing and/or MRO activities.

Extrapolation to the total 150 sites across the EEA and UK suggests EEA job losses of just under 25,800 and UK job losses of 10,920. This equates to total job losses of 36,720, of which around 12,950 are directly involved in electroplating and 23,770 are involved in linked assembly, manufacturing and/or MRO activities.

Table 5-2: SEA survey responses and extrapolations on numbers of jobs lost under the non-use scenario						
	No. Company Responses		Job losses for workers undertaking electroplating and linked treatments		Additional direct Job losses due to a cessation of manufacturing/MRO activities	
From SEA Survey	EEA	UK	EEA	UK	EEA	UK
Build-to-Print (16 sites)	13	3	170	363	**37**	**921**
Design-to-Build (19 sites)	19	1	544	465	**498**	**442**
MROs (7 sites)	4	2	1103	35	**3947**	**15**
OEM (26 sites)	19	7	4097	967	**6321**	**1959**
Total 68 sites	**55**	**13**	**5,915**	**1,830**	**10,802**	**3,337**
Job losses - Extrapolation of job losses under the non-use scenario to the estimated 150 sites undertaking electroplating treatments						
Build-to-Print (78 sites)	69	8	909	1,089	196	2,762
Design-to-Build (26 sites)	22	4	672	1,859	615	1,767
MROs (15 sites)	11	4	2,451	70	8,771	30
OEM (30 sites)	22	8	4,792	1,105	7,393	2,239
Total sites (150)	**125**	**24**	8,824	4,123	16,974	6,799

It is important to note, that these losses do not equate to 100% of the jobs at these sites, as there would not be a full cessation of activities at all sites. Instead, they represent those jobs that are linked to or dependent upon electroplating, including downstream machining, manufacturing and assembly activities. In addition, the figures do not include impacts on military MROs, given that these would not necessarily translate to "lost jobs". Although these figures appear high, they should be seen within the context of the roughly 890,000 employees (2019[71]) within the European aerospace sector and the critical importance of chromium trioxide in electroplating. Furthermore, it is important to note that there will be A&D sites that are unaffected as they do not undertake electroplating or rely on parts electroplated by suppliers/other sites in the EEA/UK.

These predicted job losses have been combined with 2018/19 Eurostat data on Gross Value Added (GVA) per employee to the EEA/UK economy as part of calculating the economic losses under the non-use scenario. A weighted GVA has been used for BtP and DtB suppliers and NACE code specific GVAs have been used for OEMs and MROs. The resulting estimated losses in GVA are given in **Table 5-3**.

The estimated losses in GVA equate to:

- €2,296 million per annum and €782 million per annum for the 125 EEA and 25 UK sites respectively due to the cessation of electroplating and related pre- and post-surface treatments and related assembly and manufacturing activities.

The magnitude of these GVA losses reflects the fact that use of chromium trioxide in electroplating takes place across a large number of sites in the EEA/UK, including large numbers of BtP suppliers.

For comparison, turnover for the EU A&D industry is around €259 billion[72] per annum, while that for the UK A&D sector is around €57 billion (£50 billion) in 2020[73]. Thus, although these figures appear high, they are considered to be underestimates by the ADCR members (particularly the OEMs) given the potential for much larger segments of the sector to move outside the EEA /UK should chromate-based electroplating no longer be permitted.

In order to convert these GVA losses to an estimate of lost operating surplus (as a measure of lost profits), personnel costs associated with each lost job are subtracted. The results of this calculation are given in **Table 5-4**. Personnel costs are based on Eurostat data for the relevant NACE codes, with an average weighted personnel cost adopted for all BtP and DtB sites; the Eurostat figures on personnel costs for OEMs and MROs are adopted in these cases.

The estimated operating surplus losses equate to:

- €710 million per annum across the 125 EEA sites and €249 million per annum across the 25 UK sites.

71 Statista 2022: https://www.statista.com/statistics/638671/european-aerospace-defense-employment-figures/

72 https://www.statista.com/topics/4130/european-aerospace-industry/#topicHeader__wrapper

73 https://www.statista.com/statistics/625786/uk-aerospace-defense-security-space-sectors-turnover/

Table 5-3: GVA losses per annum under the non-use scenario						
	GVA per worker assumed by role		GVA lost due to job losses of workers undertaking electroplating and linked treatments - € million		Additional GVA lost due to loss of all jobs including electroplating, linked treatments and cessation of manufacturing/MRO activities - € million	
	EEA	UK	EEA	UK	EEA	UK
Build-to-Print (16 sites)	59,488*	59,488*	10.1	21.6	2.2	54.8
Design-to-Build (19 sites)	59,488*	59,488	32.4	27.6	29.6	26.3
MROs (7 sites)	85,000	85,000	93.8	3.0	335.5	1.3
OEM (26 sites)	98,500	98,500	403.6	95.2	622.6	193.0
Total 68 sites			540.0	147.5	989.9	275.3
		Total EU	**€ 1529 million per annum**			
		Total UK	**€ 423 million per annum**			
GVA losses - Extrapolation to the estimated 125 EEA and 25 UK sites undertaking electroplating treatments						
Build-to-Print (78 sites)	59,488*	59,488*	54.1	64.8	11.6	164.3
Design-to-Build (26 sites)	59,488*	59,488*	40.0	110.6	36.6	105.1
MROs (15 sites)	85,000	85,000	208.3	5.9	745.5	2.6
OEM (30 sites)	98,500	98,500	472.0	108.9	728.2	220.5
Total sites (150)			774.4	290.1	1,522.0	492.5
		Total EEA	**€ 2,296 million per annum**			
		Total UK	**€ 783 million per annum**			
***Weighted average GVA calculated for Build-to-Print and Design-to-Build companies as the GVA multiplied by the NACE code counts across responding companies, divided by the total number of relevant companies. MRO and OEM GVA figures direct from Eurostat (2018) for EU/UK as available.**						

Table 5-4: Implied GVA-based gross operating surplus losses under the non-use scenario						
	Total GVA losses- € millions per annum		Total personnel costs associated with lost jobs - € millions per annum*		Implied operating surplus losses € millions per annum	
	EEA	UK	EEA	UK	EEA	UK
Build-to-Print (16 sites)	12.3	76.4	8.1	50.0	4.2	26.3
Design-to-Build (19 sites)	62.0	53.9	40.6	35.3	21.4	18.6
MROs (7 sites)	429.3	4.3	284.8	2.8	144.4	1.4
OEM (26 sites)	1,026.2	288.2	735.5	206.6	290.7	81.6
Total 68 sites	1,529.7	422.8	1,069.0	294.8	460.7	128.0
Operating surplus losses - Extrapolation to the estimated 125 EEA and 25 UK sites undertaking electroplating treatments						
Build-to-Print (78 sites)	65.7	229.1	43.0	150.1	22.7	79.0
Design-to-Build (26 sites)	76.5	215.7	50.2	141.3	26.4	74.4
MROs (15 sites)	953.9	8.5	632.9	5.6	321.0	2.9
OEM (30 sites)	1,200.2	329.4	860.2	236.1	340.0	93.3
Total sites (150)	2,296.3	782.7	1,586.4	533.1	710.0	249.5
*Weighted personnel costs calculated for Build-to-Print and Design-to-Build companies as the GVA multiplied by the NACE code counts across responding companies, divided by the total number of relevant companies. MRO and OEM GVA figures direct from Eurostat (2018) for EU/UK as available.						

5.2.2.4 Estimates based on lost turnover

The SEA questionnaire also asked companies to provide information on the impacts that a refused authorisation would have on turnover/revenues. Fewer companies provided a response to this question, although the information provided together with the most likely NUS for the DtBs, OEMs and MROs enables estimates of likely percentages of turnover lost by role to be developed. These estimates take into account the number of companies indicating that they also carry out activities other than chromate-based electroplating for the A&D sector, as well as surface treatment and other processes for other sectors.

Total revenue estimates are based on Eurostat data by NACE code with weighted averages used for BtPs and DtBs and NACE code specific data used for OEMs and MROs. Note that the weighted averages exclude micro-enterprises as few suppliers to the sector will fall into this size category. Gross operating surplus losses are then calculated using Eurostat data by NACE code. The resulting losses in profits or GOS are given in **Table 5-5**, with these equating to around €2,329 and €732 million per annum for the EEA and UK respectively.

Table 5-5: Turnover and GOS losses under the non-use scenario (based on Eurostat GOS data)

	% turnover lost	Revenues lost per annum € millions		GOS losses per annum € millions per annum	
		EEA	UK	EEA	UK
Build-to-Print (16 sites)	70%	574	132	76	17
Design-to-Build (19 sites)	40%	454	25	60	3
MROs (7 sites)	60%	214	86	21	8
OEM (26 sites)	70%	16,155	5,952	1,543	568
Total 68 sites		17,397	6,195	1,699	598
Extrapolation of turnover and GODS losses to the estimated 125 EEA and 25 UK sites undertaking electroplating					
Build-to-Print (78 sites)	70%	3,066	397	404	52
Design-to-Build (26 sites)	40%	561	101	74	13
MROs (15 sites)	60%	476	171	47	17
OEM (30 sites)	70%	18,895	6,802	1,804	650
Total sites (150)		22,997	7,472	2,329	732

*Weighted average GVA calculated for Build-to-Print and Design-to-Build companies as the GVA multiplied by the NACE code counts across responding companies, divided by the total number of relevant companies. MRO and OEM GVA figures direct from Eurostat (2018) for EU/UK as available.

5.2.2.5 Comparison of profit loss estimates

For comparison purposes, the two approaches result in the following upper and lower bound estimates of losses in gross operating surplus/profits:

- Losses in GVA and hence in implied gross operating surpluses:
  - Losses of €710 million per annum for the EEA
  - Losses of €249 million per annum for the UK

- Losses in turnover and hence losses in gross operating surpluses:
  - Losses of €2,329 million per annum for the EEA
  - Losses of €732 million per annum for the UK

The two sets of figures are used in this SEA to provide lower and upper bound estimates of losses in producer surplus, with the ratios between the two sets of estimates for the different roles shown in **Table 5-6**. It is important to note that these losses apply to commercial enterprises only. No data was provided by any of the military organisations reliant upon the continued use of chromate-based electroplating which could be used in this analysis. These organisations simply stated that they would have to cease undertaking MRO related activities in their home country, resulting in severe impacts on their national air forces (in particular) and maintenance of other defence equipment.

Table 5-6: Comparison of profit loss estimates

	Total job losses		% turnover lost		Ratio of lost profits based on turnover to lost operating surplus based on jobs (based on €billions lost)	
	EEA	UK	EEA	UK	EEA	UK
Build-to-Print (78 sites)	1,105	3,851	70%	70%	17.82	0.66
Design-to-Build (26 sites)	1,287	3,626	40%	40%	2.80	0.18
MROs (15 sites)	11,222	100	60%	60%	0.15	5.87
OEMs (30 sites)	12,185	3,344	70%	70%	5.31	6.96
Total sites (150)	25,798	10,921	€2.3 billion	€732 million	3.28	2.93

5.2.2.6 Offsetting profit losses and impacts on rival firms

The losses in operating surplus given above would result not only from a cessation of manufacturing activities, but also from the premature retirement of existing capital equipment. Some of this capital equipment would be replaced in any event as part of substitution, over the next four to 12 years, with any such investment in new equipment would be focused on facilitating substitution (while the capital equipment associated with the continued use of chromium trioxide over the next seven to 12 years would not be expected to be replaced).

As there are no suitable alternatives which are generally available, following SEAC's latest guidance, consideration has been given to the need to offset the profit losses for downstream users against the potential resale or scrappage value of the sector's tangible EEA and UK assets. However, given the potential scale of the impacts of a refused authorisation for the sector as a whole, any possible market for redundant equipment is likely to be overwhelmed by the number of sites ceasing activities, including related processes. As a result, it is not possible to estimate the potential scrappage value of equipment (e.g. immersion baths), especially as its current use for chromate-based treatments may further reduce its value.

Consultation indicates that a shift to an alternative form of electroplating is likely to require investment in new equipment for some sites and repurposing of existing equipment for other sites, depending on the alternative. For some companies there may also be a need to run two lines to accommodate customers (i.e. OEMs or Design-to-Build companies) with different requirements due to only CT being certified for use in the production of some components. However, it is not possible at the sectoral level to determine what level of new investment would be required. As a result, no costs associated with investment in new equipment are included here. Where equipment has been made redundant due to successful substitution efforts, consultees indicate that it has not been able to repurpose it due to its previous use having been based on the chromic acid; this reduces market demand for refurbishment.

Because this is a sectoral application and the ability to shift to alternatives is driven by qualification and validation by OEMs and obtaining certification approval by airworthiness authorities, the issue of potential losses incurred by rival firms undertaking electroplating using alternatives is not relevant. The OEMs determine whether or not there are alternatives that can be used, not individual downstream users. Furthermore, as previously indicated, the ADCR is a sectoral consortium and downstream user members include competitors, which may also act as suppliers to each other, while the larger companies share many of the same BtP and DtB suppliers (an estimated 15-25% overlap in suppliers exists across some OEMs). Relationships between the OEMs and BtP and DtB are developed over time and often reflect long-term commitments given the need for OEMs and DtB companies to certify their suppliers in the manufacturing of components. As a result, rival suppliers cannot readily step in and replace their production activity.

The economic losses are therefore based on consideration of losses in operating surplus/profits only. These have been estimated over three time periods in line with SEAC's new guidance for those cases where there are not suitable alternatives available in general. Discounted losses over one, two, four, seven and 12 years are given in **Table 5-7**.

As discussed earlier, these losses are based on Eurostat turnover figures for 2018 (most recently available by company size). They therefore represent an underestimate of the losses in turnover that would arise over the review period under the non-use scenario, given the anticipated level of future growth in turnover for the sector due to the importance of the EEA and UK in the global manufacture of aerospace and defence products (as highlighted by the publicly available forecasts of the demand for new aircraft cited earlier).

Table 5-7: Discounted profit /operating surplus losses under the non-use scenario – Discounted at 4%, year 1 = 2025

	Lost EBITDA/Profit € millions		GVA-based Operating Surplus Losses € millions	
	EEA	UK	EEA	UK
1-year profit losses (2025)	2,348	735	711	251
2-year profit losses (2026)	4,392	1,381	1,336	342
4-year profit losses (2028)	8,522	2,667	2,579	912
7-year profit losses (2031)	14,091	4,409	4,265	1,508
12-year profit losses (2036)	22,034	6,894	6,668	2,359

5.2.2.7 Other impacts on Aerospace and Defence Companies

Under the non-use scenario there would be an enormous impact on the A&D sector in the EEA/UK, leading to a second wave of negative impacts on the EEA market. These impacts have not been quantified here but would include as a minimum:

- Cancelled future orders and loss of contracts for new products if supplies are significantly interrupted;
- Customer penalties for late/missed delivery of products and/or maintenance operations on products in service (aircraft on ground);

- Extended durations of maintenance, repair and overhaul operations for products in service leading to e.g. “aircraft on the ground” (AoG) and other out-of-service final products, with consequent penalties and additional impacts on turnover;
- Increased logistical costs; and
- Reputational damages due to late delivery or cancelled orders.

5.2.3 Economic impacts on competitors

5.2.3.1 Competitors in the EEA/UK

This Review Report has been prepared so as to enable the continued use of the CT in electroplating across the entirety of the EEA and UK aerospace and defence sectors. It is non-exclusive in this respect. It has been funded by the major (global) OEMs and DtB manufacturers in the EEA and the UK, with additional support provided by their suppliers and by Ministries of Defence, so as to ensure functioning supply chains for their operations.

As a result, there should be no economic impacts on competitors, especially as the major global OEMs and DtBs act as the major design owners which determine the ability of all suppliers to move to an alternative. As design owners they validate qualify and certify components and products with new alternatives and gain new approvals (e.g. approvals from EASA, ESA or MoDs), Once these design owners have certified new alternatives in the manufacture of parts and components, these alternatives will be implemented throughout their value chain.

Under the non-use scenario, such work would continue outside the EEA/UK, to the detriment of smaller EEA/UK BtP suppliers in particular.

5.2.3.2 Competitors outside the EEA/UK

Under the NUS, it is likely that some of the major OEMs and DtB suppliers would move outside the EEA/UK, creating new supply chains involving BtP and MROs. This would be to the detriment of existing EEA/UK suppliers but to the advantage of competitors outside the EEA/UK. These competitors would gain a competitive advantage due to their ability to continue to perform CT based electroplating and due to their proximity to the OEMs and DtB, thus minimising logistic and transport issues.

5.2.4 Wider socio-economic impacts

5.2.4.1 Impacts on air transport

Under the non-use scenario there would be significant impacts on the ability of MROs to undertake repairs and to follow normal maintenance and overhaul schedules. As indicated previously, MROs are legally bound to adhere to the requirements set out in the OEMs’ manuals under airworthiness and military safety requirements. Where maintenance or overhaul activities would require chromate-based electroplating, they would have to be performed outside the EEA/UK until the OEMs have gained approvals and certifications for the use of alternatives on components and have adapted the manuals setting out maintenance and overhaul instructions.

If an aircraft needs unscheduled repairs (i.e. flightline or “on-wing” repairs), it will be grounded at the airport until these take place due to airworthiness constraints. This would result in AOGs and could result in an aircraft having to be dis-assembled and transported outside the EEA/UK for repairs, with dramatic financial and environmental impacts.

Should MRO facilities be relocated outside the EEA/UK, airlines will also experience additional delays to routine aircraft maintenance due to transport requirements and capacity constraints at MRO facilities outside the EU. Indeed, it may take some time to build up capacity to accommodate additional demand from EU-based operators, potentially resulting in a large number of aircraft being grounded until maintenance checks can be completed.

As a result, airlines would need to have additional spare components/engines/planes to account for the added time that aircraft would be out of commission due to extended MRO times. Airports may also have to build up large inventories of spare components to replace products (including e.g. spare engines, aircraft) that currently can be repaired, with this going against the desire to ensure sustainability within the sector.

The need to have maintenance carried out outside the EEA/UK would also lead to additional operational costs being incurred through increased fuel use. Small planes (e.g. business jets) that do not have the fuel capacity or airworthiness approvals for long haul flights would need to make multiple stops enroute to non-EEA MRO facilities and back to the EEA/UK. The impacts for larger aircraft would also be significant. For example, flying from Western Europe to Turkey or Morocco adds approximately 3,000 km each way and for a Boeing 737 this would take slightly less than four hours. For an airline which has 50 aircraft requiring an annual “D check” (heavy maintenance inspection of the majority of components, carried out every 6-10 years), this would involve 400 hours of flight time (return trip) or 20 days of foregone revenue, equivalent to €1.4 million. Scaling this up to the EEA passenger aircraft fleet, which stands at approximately 6,700, suggests lost revenues in the tens of millions per annum just due to the need to have around 700 aircraft which require a “D check” each year. Using the above estimate for a fleet of 50 aircraft, this would amount to €20 million in revenue lost by European airlines for “D checks” alone. This figure excludes the costs of fuel and personnel, as well as the fact that additional flights bring forward maintenance interval requirements and impact on the total lifespan of an aircraft

In addition, based on a leasing cost for a large passenger jet of around $500,000/month in 2021 (€421,500, £362,250)[74], the leasing costs alone of a plane being out of service would be roughly €14,000/£12,100 per day. On top of this will be the additional losses in revenues from not being able to transport passengers or cargo. For example, an Airbus A320 carries from 300 to 410 paying customers on one long-haul flight per day. If tickets cost on average €650 (£560) per customer (assuming 350 customers), the revenue lost due to being ‘out of action’ for one day amounts to €227,500 (£195,500). As a result, the cost of extending the period over which a plane is out of service for repair or maintenance reasons may lead to significant new costs for airlines, delays for passengers and in the transport of cargo, as well as subsequent effects for GDP and jobs due to planes being out of service for longer.

ICAO reported[75] a -49 to -50% decline in world total passengers in 2021 compared to 2019. In 2020, figures for Europe show a -58% decline in passenger capacity, -769 million passengers and a revenue loss of -100 billion USD. In addition, COVID-19 caused a 74% decrease in passenger demand for international travel in 2020 compared to 2019. The trend though is for the aircraft industry to

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74 https://www.statista.com/statistics/1258900/aircraft-lease-rates-aircraft-model/#statisticContainer

75 https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf

continue expanding globally, with pre-covid estimates suggesting that demand for air transport would increase by an average of 4.3% per annum over the next 20 years, as illustrated in **Figure 5–2** below. Similar growth is expected in air freight transport. If this growth path were to be achieved, by 2036 the air transport industry would contribute 15.5 million in direct jobs and $1.5 trillion of GDP to the world economy. Once the impacts of global tourism are taken into account, these numbers could rise to 97.8 million jobs and $5.7 trillion in GDP.

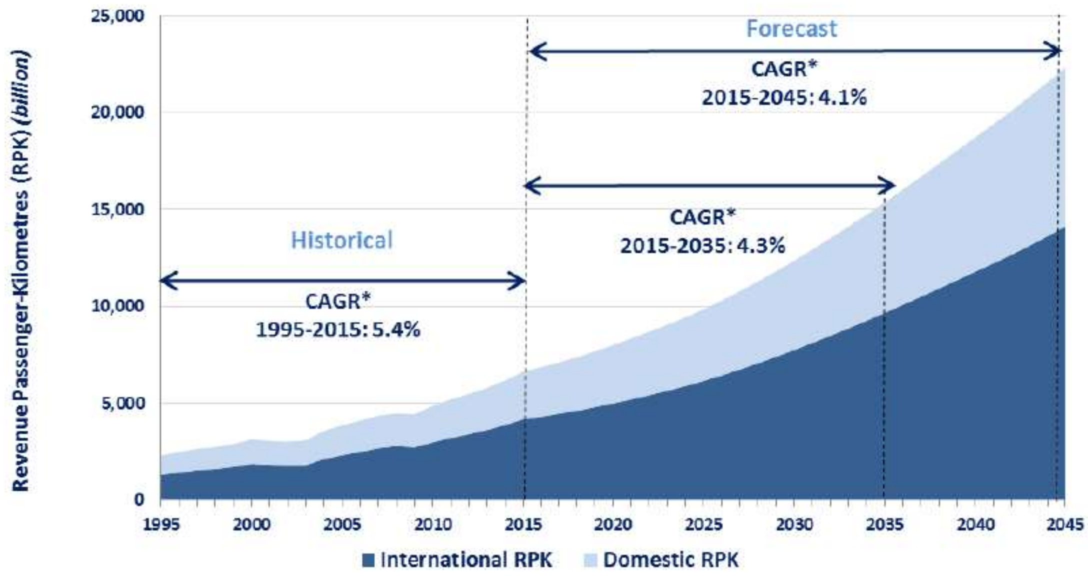

Figure 5–2: Forecast compound annual growth rates – Revenue Passenger-kilometres

Post Covid-19, projections are for a lower rate of increase in air traffic. A growth rate between 2019 and 2040 of around 3.9% CAGR is expected according to data available on the Airbus website.[76] The impact of COVID has resulted in an expected 2-year lag in growth, but the forecast remains unchanged with passenger numbers expecting to increase in line with the forecasts. This growth rate is relevant to global air traffic, with Europe expected to realise a lower compound annual growth rate of about 3.3% for total traffic[77] (covering inter-regional and intra-regional/domestic) for the period between 2018 to 2038.

This level of growth in EU air traffic, together with the jobs and contributions to GDP that it would bring, could be impacted under the NUS. In particular, impacts on the ability of MROs to undertake repairs and carry out maintenance where this would require the use of chromate-based electroplating to ensure the continued airworthiness of aircraft could impact on the realisation of such growth. No quantitative estimate of the level of impact can be provided, but it is clear that the closure of EU-based MRO operations in particular could impact on the availability of aircraft and hence passenger and freight transport until substitution has taken place as expected over the requested review period (unless airlines responded by buying more planes or stockpiling of components, which would inevitably give rise to increases due to the costs of holding spares and/or bringing spare planes on-line).

[76] Airbus (undated): Airbus Global Market Forecast 2021 – 2040. Available at: Global Market Forecast | Airbus

[77] https://www.statista.com/statistics/1094689/annual-growth-rate-air-passenger-traffic-europe/

5.2.4.2 Defence-related impacts

Defence related impacts under the NUS would have two dimensions: impacts on military forces; and impacts on companies acting as suppliers to military forces.

Three national Ministries of Defence (MoDs – two in the EEA and the UK MoD) have provided direct support to the ADCR out of the concern that the non-Authorisation of electroplating could have a negative impact on their activities, while another has provided information to assist in preparation of this Review Report. In addition, MROs providing services to a further two MODs located in the EEA have supported the ADCR so as to ensure that they are able to continue to maintain and repair military aircraft, ships and ground-based systems into the future. The implications of having to cease these activities are significant. Military equipment which could not be maintained to appropriate safety standards would have to be removed from service, with this also impacting on internal security services and emergency services. Not only would this impact on the availability of key equipment in the case of a military emergency, but it would also affect the size of potential operational forces.

It is also worth noting that Governments are likely to be reluctant to send military aircraft to MRO facilities located in non-EU countries, although the US, Canada and Turkey are NATO members, and as such may be suitable candidates to service European military aircraft. There would be impacts on mission readiness if repairs cannot be done locally. This could, in fact, be far more impactful than the economic impacts linked to the defence sector.

As a result, it is likely that under the NUS, companies manufacturing components for and servicing military products would have to apply for defence exemptions; although for some companies, the turnover generated by military contracts alone may not be sufficient to maintain current production levels and it may not be economically feasible to operate dual manufacturing lines for military and civilian customers.

Companies in the European defence sector represent a turnover of nearly €100 billion and make a major contribution to the wider economy[78]. The sector directly employs more than 500,000 people of which more than 50% are highly skilled. The industry also generates an estimated further 1.2 million jobs indirectly. In addition, investments in the defence sector have a significant economic multiplier effect in terms of creation of spin-offs and technology transfers to other sectors, as well as the creation of jobs. For example, according to an external evaluation of the European Union's Seventh Framework Programme, through short-term leverage effect and long-term multiplier effects each euro spent by the Seventh Framework Programme (FP7) generated approximately an additional €11 billion of estimated direct and indirect economic effects through innovations, new technologies and products.[79]If the manufacture and servicing of military aircraft and other derivative defence products was to move out of the EEA/UK under the NUS, as indicated by OEMs and Design-to-Build companies as the most likely response, then these multiplier effects would be lost to the EEA economy. In addition, the ability of the EEA/UK to benefit from some of the innovations and technological advances in products ahead of other countries could be lost, if the shift in manufacturing remains permanent and extends to new products.

[78] https://ec.europa.eu/commission/presscorner/detail/de/MEMO_16_146

[79] https://www.evropskyvyzkum.cz/cs/storage/bf5134fec407f6e005288c0e2631ad232c38c013?uid=bf5134fec407f6e005288c0e2631ad232c38c013

However, under the NUS, companies manufacturing components for defence and servicing military aircraft and other derivative defence products would most likely apply for defence exemptions; although for some companies, the turnover generated by military contracts alone may not be sufficient to maintain current production levels and it may not be economically feasible to operate dual manufacturing lines for military and civilian customers.

If Governments did allow the manufacture and servicing of military aircraft and other defence products to move out of the EEA/UK under the NUS, then some proportion of such multiplier effects would be lost to the EEA/UK economy. In addition, the ability of the EEA/UK to benefit from some of the innovations and technological advances in products ahead of other countries could be lost, if the shift in manufacturing remains permanent and extends to new products.

5.2.5 Summary of economic impacts

Table 5-8 provides a summary of the economic impacts under the non-use scenario.

Table 5-8: Summary of economic impacts under the non-use scenario over the requested Review Period (12 years, @ 4%)

Economic operator	Quantitative	Qualitative
Applicants	• See formulation SEA	Not assessed
A&D companies	• Annualised lost profits: ○ EEA: €708 – 2,329 million ○ UK: €182 – 732 million • 12-year lost profits: ○ EEA: €6,646 – 21,854 million ○ UK: €1,704 – 6,870 million	Relocation costs, impacts on R&D, impacts on supply chain coherence, impacts on future growth in the sector
Competitors	Not anticipated due to sectoral coverage of the application Non-EEA/UK based suppliers may win new contracts should EEA/UK based A&D companies sub-contract overseas; the potential value of such sub-contracts cannot be estimated	Not anticipated due to sectoral coverage of the application
Customers and wider economic effects	Not assessed	• Impacts on airlines, air passengers, customers, cargo and emergency services, and thus society as a whole. • Impacts on military forces' operational capacity and mission readiness • Lost employment multiplier effects due to impacts on civil aviation and loss of defence sector spending • Loss of spin-off effects – innovation and new technologies

5.3 Environmental impacts under non-use

The most plausible non-use scenario in the event of a non-renewal of the Authorisation to use chromium trioxide inside the EEA/UK - even if it may not be practical and would involve huge levels of investment - would be to shift the activity involving use of chromium trioxide to another country (outside the EEA or UK).

Under this scenario, as noted above, the environmental impacts would be real and the effects enormous. If manufacturing activities using chromium trioxide and not using chromium trioxide are separated on both sides of the European border, huge logistics and transport related requirements would have to be introduced with dramatic impacts on the aerospace and defence sectors' environmental footprint.

For MRO activities, each time an aircraft would need a minor repair requiring chromate-based electroplating use, it would force the manufacturer to go to a non-European site. In the case of a major repair, aircraft that could not fly would become stranded or, less likely, would have to be dis-assembled for transport to a non-European site. Some stranded final products would become obsolete prematurely, due to the lack of the components needed for their maintenance and repair. This would go against the principles underlying the Circular Economy and the sustainable use of raw materials, by limiting the ability of the sector to repair and re-use components and assemblies.

Today, the civil aviation industry strives to develop new technologies to reduce the amount of CO2 emissions by 15 - 20% on each generation of in-service aircraft (make aircraft movements emission-free), since it is well aware that aviation continues to grow significantly.

Even despite the impact that the COVID-19 pandemic had on air traffic and had the whole civil aviation industry, aviation is expected to double in the next 20 years. Consequently, a refused authorisation renewal would lead to aircraft manufacturing and MRO activities involving chromate uses to move outside the EEA. In addition to the socio-economic consequences this would have, the drastic increase in CO_2 emissions, would outweigh all the benefits achieved by aviation efforts to reduce fuel consumption and CO2 emissions of in-service aircrafts.

The non-use scenario would also result in some existing aircraft and equipment becoming redundant prematurely, due to the lack of the components needed for their maintenance and repair. This outcome would work against the Circular Economy and the sustainable use of raw materials, by limiting the ability of the sector to repair and re-use components and products.

5.4 Social impacts

5.4.1 Direct and Indirect Job losses

5.4.1.1 Estimated level of job losses

The main social costs expected under the NUS are the redundancies that would be expected to result from the cessation of production activities (all or some) and the closure and relocation of sites. As indicated in the assessment of economic costs, the estimated reduction in job losses is based on responses to the SEA questionnaires covering 64 sites in total. Direct job losses will impact on workers at the site involved in electroplating and linked pre-treatment and post-treatment processes as well those involved in subsequent production steps and related activities (e.g. lab workers, etc.). These are all referred to here as direct job losses (for avoidance with confusion of multiplier effects).

While redundant workers are expected to face a period of unemployment, in line with ECHA's guidance it is assumed that such a period would be only temporary. However, the length of the average duration of unemployment varies greatly across European countries, as do the costs associated with it.

It should be noted that the ECHA methodology has been followed here despite the fact that the impacts across the A&D sector may make it difficult for workers to find another job, especially as there may be a skill mismatch if there are large scale levels of redundancies).

Estimates of the direct job losses that would arise at downstream users' sites under the NUS were presented above. For ease of reference, the totals are repeated in **Table 5-9** below. The magnitude of these figures reflects the importance of electroplating to the production of landing gear and other components, as well as to maintenance and repairs of such components at a subset of MRO facilities. No consideration is given to job losses at those companies providing services that are contracted to provide cleaning and other services to the BtPs, DtBs, MROs and OEMs.

As context, the civil aeronautics industry alone employees around 405,000 people in the EU, with the defence sector employing more than 500,000 and supporting a further 1.2 million[80].

Table 5-9: Predicted job losses in aerospace companies under the NUS

Role	Job losses directly linked to use of the chromates		Additional job losses due to cessation of other manufacturing		Total A&D job losses under the NUS	
	EEA	UK	EEA	UK	EEA	UK
Build-to-Print (78 sites)	909	1,089	196	2,762	1,105	3,851
Design-to-Build (26 sites)	613	207	585	103	1,198	310
MROs (15 sites)	2,451	70	8,771	30	11,222	100
OEM/30 sites)	4,792	1,105	7,393	2,239	12,185	3,344
Total sites (150)	8,765	2,471	16,945	5,135	25,709	7,605

5.4.2 Monetary valuation of job losses

The method for estimating the social costs of unemployment follows that recommended by ECHA (Dubourg, 2016[81]).

Costs of unemployment are calculated by adding up lost output which is equivalent to the pre-displacement gross salary throughout the period out of work, search costs, rehiring costs for employers and scarring effects, and deducting the value of leisure time.

Dubourg (2016) estimated different ratios of the social cost per job loss over the annual pre-displacement wage for European countries and the EU-28 as a whole that varies according to the mean

80 https://www.eudsp.eu/event_images/Downloads/Defence%20Careers%20brochure_1.pdf

81 Dubourg, R (2016): Valuing the social costs of job losses in applications for authorisation. Available at: https://echa.europa.eu/documents/10162/13555/unemployment_report_en.pdf/e0e5b4c2-66e9-4bb8-b125-29a460720554

duration of unemployment. These vary by country, with the mean duration of unemployment weighted by the number of employees for each country relevant to aerospace and defence sector productions sites varying from seven months to 1.6 years.

These figures are combined with the ratio of social costs per job loss provided in Dubourg (2016) and annual wages to calculate the social costs per lost job. Data were collected in the SEA questionnaire on the average salary for workers involved in the use of chromium trioxide. The typical range given is from €30k to 50k, rising to an average maximum of around €76k, across all of the companies and locations. For the purposes of these calculations, a figure of €40k has been adopted and applied across all locations and job losses. This figure is based on the NACE code data provided by companies but will underestimate the average salary given that A&D jobs in the prime OEMs and DtB companies are higher paid than those in other industries.

The resulting estimates of the social costs of unemployment are given in **Table 5-10** based on consideration of the geographic distribution Article 66 notifications and the location of suppliers to the ADCR's OEMs and DtB companies, as well as MROs. The social costs are estimated at €2.8 billion or the EEA countries and around €760 million for the UK.

Table 5-10: Social Cost of Unemployment – Job losses at A&D companies under the NUS

Country	Employment losses due to cessation or relocation of manufacturing	Social costs of unemployment (€)
France	2,571	325,996,013
Poland	1,800	169,168,278
Italy	5,913	716,677,040
Germany	7,456	775,397,457
Spain	2,057	230,356,804
Czech Republic	1,028	112,710,294
Netherlands	514	48,333,794
Sweden	514	45,865,685
Norway	257	27,971,898
Belgium	514	98,346,528
Finland	129	8,946,894
Austria	514	49,567,848
Denmark	257	17,996,625
Romania	257	24,578,248
Ireland	129	12,597,638
Hungary	386	42,420,617
Malta	129	10,438,043
Portugal	129	14,551,557
Slovakia	257	26,737,843
Bulgaria	257	23,035,680
Greece	386	40,415,279
Slovenia	129	10,952,232
Croatia	129	12,289,124
Total EEA	**25,709**	**2,822,110,063**
United Kingdom	7,605	762,956,751
Total	**33,315**	**3,608,308,170**

5.4.3 Wider indirect and induced job losses

5.4.3.1 Aerospace and defence related multiplier effects

Employment in one sector is often the input to employment in another sector, so that fluctuations in employment of the latter will inevitably affect the former. Under the NUS, there could be significant wider impacts on jobs given the likelihood that some of the largest players in the EEA/UK aerospace and defence sector would relocate their activities elsewhere with a partial or full cessation of manufacturing in the EEA/UK.

A UK Country Report on the "Economic Benefits from Air Transport in the UK" produced by Oxford Economics (2014) indicates the following with respect to the aerospace sector's contribution to UK employment in 2012:

- Indirect employment effects: 139,000 jobs implying a multiplier effect of 1.36 indirect jobs for every direct job;
- Induced employment effects: 86,000 jobs implying an additional multiplier effect of 0.84 induced jobs for every direct job.

Indirect employment effects will to a degree be captured by the estimates of lost jobs presented in **Table 4-20** given that it includes the loss of jobs in suppliers to the aerospace OEMs and Design and Build companies. It excludes however other service providers to these companies whose services would no longer be required. Induced effects are not captured by the above estimates and an employment multiplier of 0.84 suggests that they may be significant given the predicted numbers of jobs that would be lost across the key countries in which aerospace-related manufacturing takes place.

The loss of jobs within those companies that serve the defence industry would have their own multiplier effects. The external evaluation of FP7 referenced above[82] quotes an employment multiplier of between 2.2 to 2.4, with this covering both indirect and induced employment effects. The sector is identified as bringing a major contribution to the wider economy.

To successfully compete at a global level, the European and UK A&D industries have formed regional and industry clusters that includes local and national government partners. The clusters are part of the European Aerospace Cluster Partnership[83](EACP) which focuses on the exchange of experiences concerning both cluster policy and the implementation of effective solutions needed to address various challenges faced by the partners. It has members located in 44 aerospace clusters across 18 countries, thus covering the entire aerospace value chain in Europe. **Figure 5-3** below is a "snip" taken from the EACP website highlighting the location of these different hubs across Europe, to provide an indication of where effects may be experienced at the regional level.

Under the non-use scenario, the economic impact on each region could have severe consequences. For example, Aerospace Wales consists of over 180 members which employ 23,000 employees with a turnover of over £6.5 billion in Wales, while the Andalucía Aerospace Cluster has over 37 members,

[82] European Commission (2017): Issue papers for the High Level Group on maximising the impact of EU research and innovation programmes. Prepared by the Research and Innovation DGs. Available at: https://www.evropskyvyzkum.cz/cs/storage/bf5134fec407f6e005288c0e2631ad232c38c013?uid=bf5134fec407f6e005288c0e2631ad232c38c013

[83] https://www.eacp-aero.eu/about-eacp/member-chart.html

16,000 employees with over €2.5 billion turnover (See Annex 2). Both of these clusters are an essential part of the local economy.

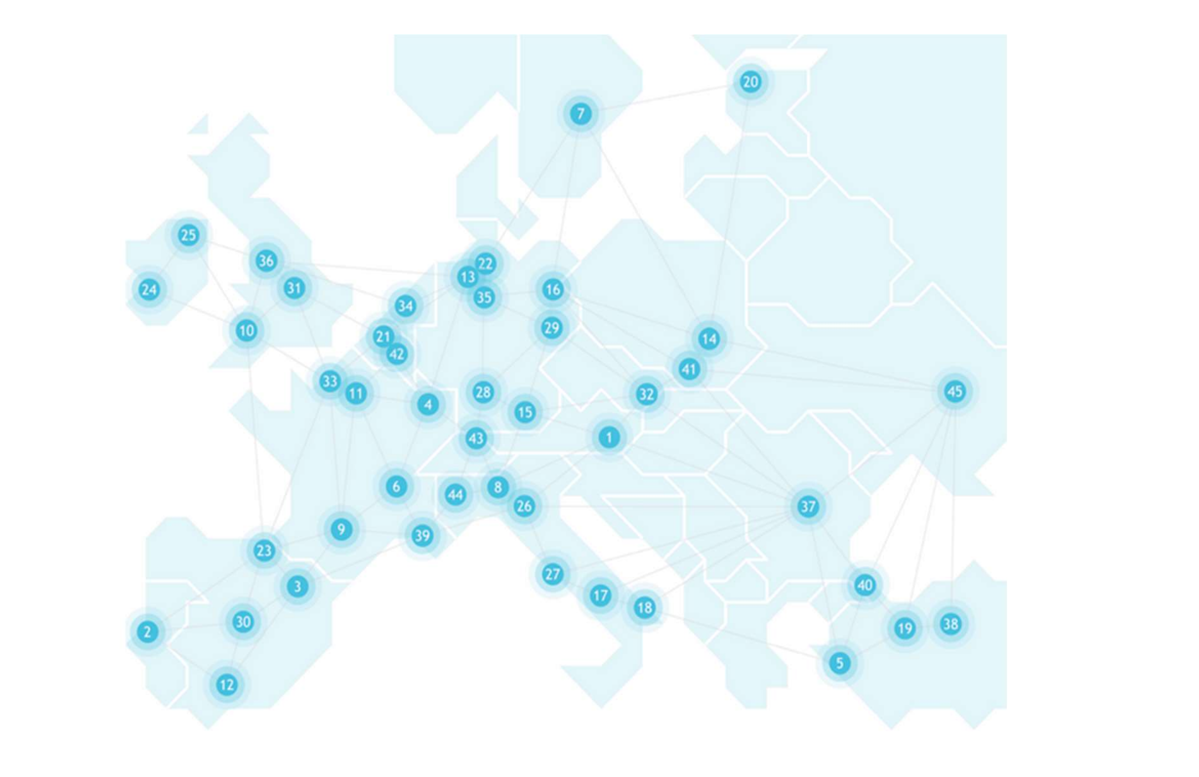

Figure 5-3: Aerospace clusters across Europe
Source: https://www.eacp-aero.eu/about-eacp/member-chart.html

5.4.3.2 Air transport multiplier effects

A 2019 "Aviation Benefits Report"[84] produced by a high-level group formed by the International Civil Aviation Organisation (ICAO) provides an assessment of the economic impacts of the aviation sector. These are linked to its direct impact as well as indirect, induced and catalytic effects. At a regional level, it is estimated that air transport supports 12.2 million jobs in Europe. 2.6 million of these jobs are direct within the aviation sector, with the remaining 9.6 million stemming indirectly from the aviation sector or relating to induced or catalytic effects.

Clearly not all these jobs would be impacted under the NUS, although some impact would be expected should there be reductions in the number of flights, increased delays and other effects from the loss of EEA/UK based MRO activities in particular.

[84] Published by the ACI, CANSO, IATA, ICAO and the ICCAIA, available at: https://www.icao.int/sustainability/Documents/AVIATION-BENEFITS-2019-web.pdf

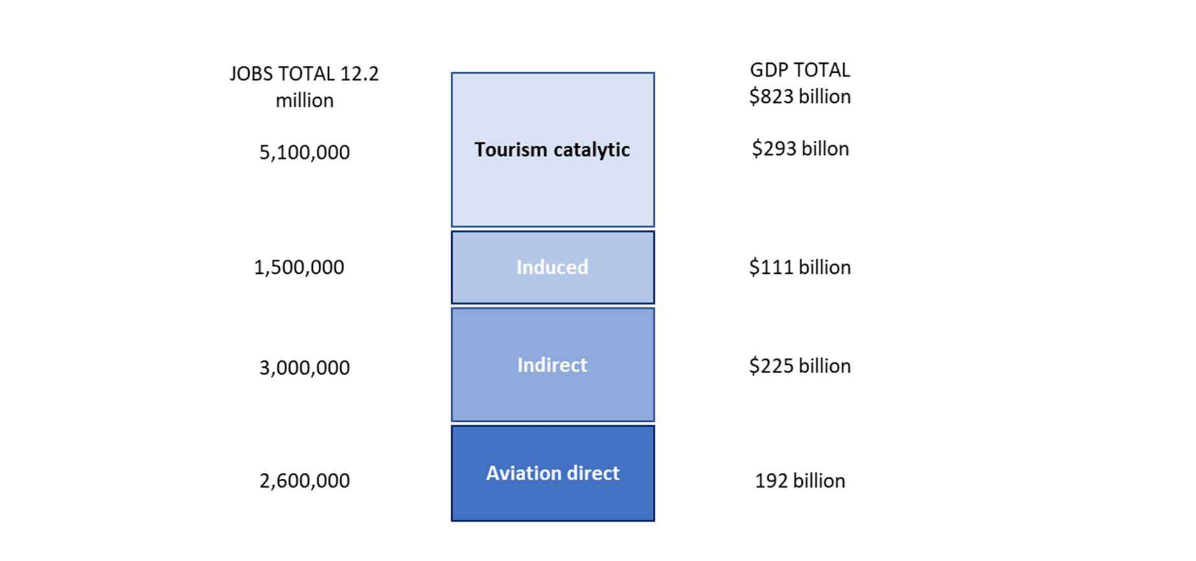

Figure 5-4: Aviation related multiplier effects

Based on: https://www.icao.int/sustainability/Documents/AVIATION-BENEFITS-2019-web.pdf

The potential employment losses associated with a decline in European aviation can be seen by reference to the impacts of COVID-19[85]. A "COVID-19 Analysis Fact Sheet" produced by Aviation Benefits Beyond Borders reports the following:

- A reduction from 2.7 direct aviation jobs in Europe supported pre-COVID to 2.1 million jobs post-COVID (i.e. at the end of 2021); and
- 13.5 million jobs in supported employment pre-COVID in Europe to 8.1 million at the end of 2021.

Although one would not expect the losses in supported employment (i.e. indirect, induced and catalytic effects) to be as great, it is clear that a disruption to civil aviation could have significant employment impacts.

5.4.4 Summary of social impacts

In summary, the social impacts that would arise under the NUS include the following:

- Direct job losses:
  - Around 25,709 jobs in the EEA due to the loss of electroplating, linked treatment process and assembly or manufacturing activities, and
  - Around 7,605 jobs in the UK due to the loss of electroplating, linked treatment process and assembly or manufacturing activities;
- Social costs of unemployment:

85 https://aviationbenefits.org/media/167482/abbb21_factsheet_covid19-1.pdf

- €2.8 billion for the EEA, and
- €760 million for the UK;

- Indirect and induced unemployment at the regional and potentially national level due to direct job losses; and
- Direct, indirect and induced job losses in air transport due to disruption of passenger and cargo services.

5.5 Combined impact assessment

Table 5-11 sets out a summary of the societal costs associated with the non-use scenario, to aid in preparation of the combined impact assessment which follows in Section 6.3. Figures are provided as annualised values and as present values over a two-year period as per ECHA's latest guidance; note that restricting losses to only those occurring over the first two years of non-use will significantly underestimate the profit losses to the A&D companies as well as the applicants. All A&D companies would incur losses for at least a four-year period, with most incurring losses over the full 12-year period as design owners continue work towards development, qualification, validation, certification and implementation of substitutes.

Table 5-11: Summary of societal costs associated with the non-use scenario		
Description of major impacts	**Monetised/quantitatively assessed/qualitatively assessed impacts**	
1. Monetised impacts	**PV @ 4%, 2 years**	**€ annualised values**
Producer surplus loss due to ceasing the use applied for: Impacts on applicants - Lost profits EEA - Lost profits UK Impacts on A&D companies: - Lost profits EEA - Lost profits UK	Applicants: See formulation SEA A&D companies EEA: €1,340 – 4,390 million (£1,149 – 3,777 million) UK: €340– 1,380 million (£294 – 1,187 million)	Applicants: See formulation SEA A&D companies EEA: €710 – 2,330 million (£609 – 2,003 million) UK: €181– 730 million (£156 – 630 million)
Relocation or closure costs	Not monetised	Not monetised
Loss of residual value of capital	Not quantifiable	Not quantifiable
Social cost of unemployment: workers in A&D sector only[1]	EEA: €2,800 million (£2,427 million) UK: €760 million (£656 million)	EEA: €1,400 million (£1,214 million) UK: €380 million (£328 million)
Spill-over impact on surplus of alternative producers	Not assessed due to sector level impacts	Not assessed due to sector level impacts
Sum of monetised impacts	EEA: €4,160 – 7,200 million (£3,576 million – 6,204 million) UK: €1,100 – 2,140 million (£955 – 1,843 million)	EEA: €2,120 – 3,740 million (£1,823 million – 3,216 million) UK: €560– 1,100 million (£484 million – 958 million)
Additional qualitatively assessed impacts		
Impacts on A&D sector	Impacts on R&D by the A&D sector, impacts on supply chain, impacts on technological innovation	
Civilian airlines	Wider economic impacts on civil aviation, including loss of multiplier effects, impacts on airline operations, impacts on passengers including flight cancellations, ticket prices, etc.	
Ministries of Defence	Impacts on the operational availability of aircraft and equipment, premature retirement of aircraft and equipment, impacts on mission readiness	
Other sectors in the EEA	Loss of jobs due to indirect and induced effects; loss of turnover due to changes in demand for goods and services and associated multiplier effects. Loss of jobs in other sectors reliant on aeroderivative uses of the chromium trioxide, such as the energy sector (e.g. use of electroplating on turbine blades) Impacts on emergency services and their ability to respond to incidents Impacts on cargo transport	
1) Lower bound figures represent lost EBITDA estimates, upper bound lost operating surpluses. 2) Estimated using the approach set out by Dubourg		

6 Conclusion

6.1 Steps taken to identify potential alternatives

Potential alternatives to Cr(VI) for electroplating should be “generally available”[86].

Alongside the various R&D activities as described in Section 3.4.1 and information reported in academic literature and patent reports as described in Sections 3.4.3, Members of the ADCR have undertaken extensive testing into alternative technologies and processes with many programmes still ongoing. The steps taken by members in the implementation of a substitute for Cr(VI)-based electroplating are shown in **Figure 6-1** below.

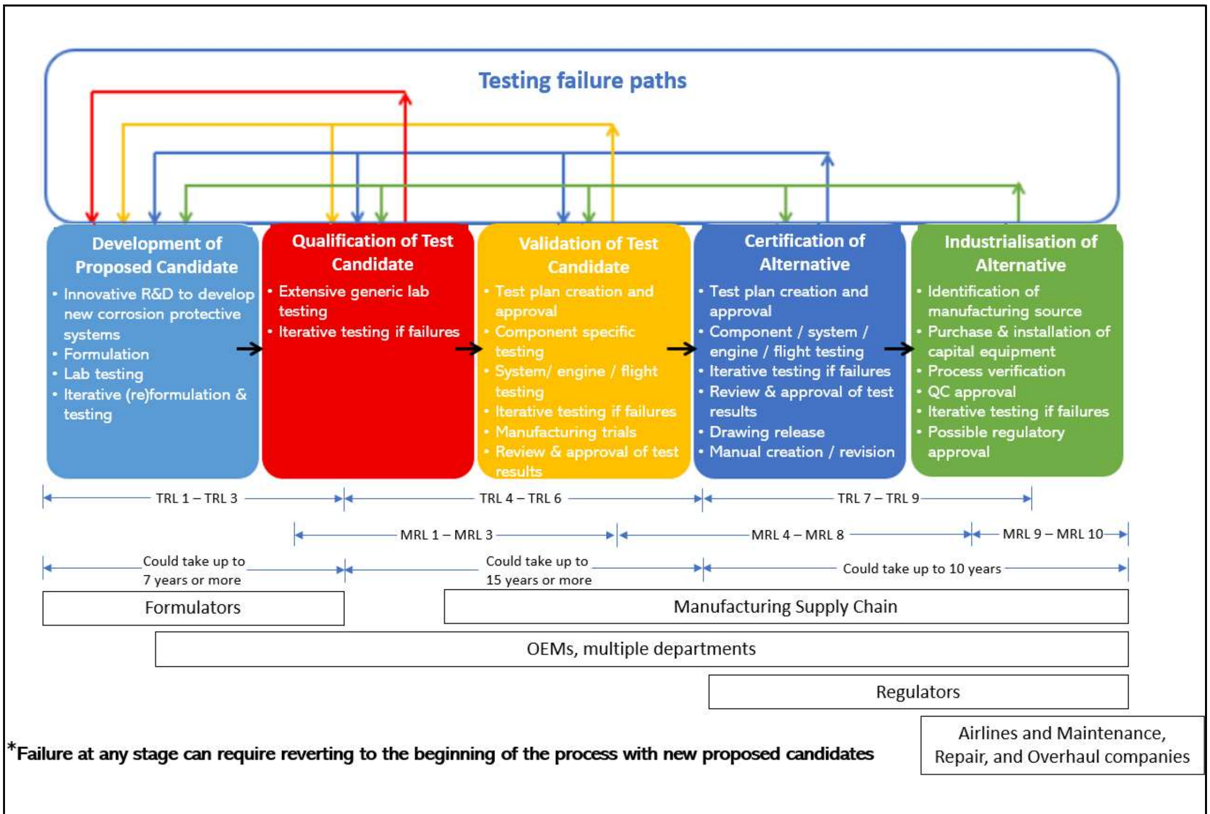

Figure 6-1: Schematic showing the key phases of the substitution process
Typical TRLs and MRLs associated with each stage, and the entities involved in each stage, are also shown. Note that failure of a proposed candidate at any stage can result in a return to a preceding stage including TRL 1. Note that failures may not become apparent until a late stage in the process.
Source: Adapted from “Use of strontium chromate in primers applied by aerospace and defence companies and their associated supply chains, Application for Authorisation 0117-01, GCCA (2017)

Activities undertaken include:

- Development of test candidates in laboratory environments up to TRL 6;
- Qualification of test candidates and suppliers including:

[86] As defined with respect to the “legal and factual requirements of placing on the market” in the EC note of 27 May, 2020, available at: 5d0f551b-92b5-3157-8fdf-f2507cf071c1 (europa.eu)

- Modification of drawings;
- Updating specifications;
- Introduction of new processes to suppliers;
- Negotiation of supplier(s) contracts.

- Demonstration of compliance followed by industrialisation; and
- Certification or approval.

6.2 The substitution plan

ADCR member companies have ongoing substitution plans in place to develop test candidates with the intent of replacing Cr(VI) in electroplating. Individual members often have multiple substitution plans within electroplating, reflecting the complexity of different components to be treated, the various substrates, and the different performance resulting from test candidates in these different situations. While there have been successes, with some members having been able to implement alternatives to Cr(VI) in certain limited situations and for certain substrates, thereby reducing their Cr(VI) usage, many technical challenges remain.

As discussed in Section 3.7.2, and shown in **Figure 6-2** below, of the 50 distinct substitution plans for electroplating assessed in this review report, 6% of them are expected to have achieved MRL 10 by September 2024. MRL 10 is the stage at which it is expected production will be in operation and there will be a significant reduction in Cr(VI) use for the components covered in that substitution plan.

The proportion of substitution plans that are expected to achieve MRL 10 is then expected to progressively increase to 32% in 2028, 50% in 2031, and 90% in 2036.

In 2031 (equivalent to seven years beyond the expiry date for the existing authorisations), while many substitution plans are expected to have successfully progressed to MRL 10 and the consortium is expected to have reduced its Cr(VI) use, an equally significant proportion (half of the substitution plans) are not expected to have achieved MRL 10 and are expected to be predominantly at the certification or industrialisation stages, with some substitution plans at earlier stages. For these substitution plans (which are from several member companies), there is still expected to be a need for the use of Cr(VI).

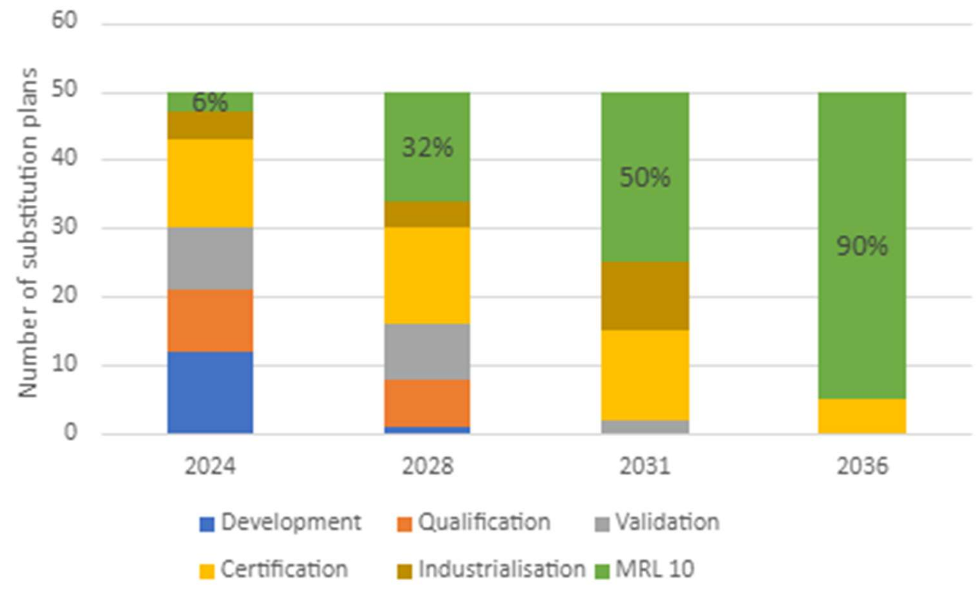

Figure 6-2: Expected progression of substitution plans for the use of Cr(VI) in electroplating, by year
The vertical axis refers to number of substitution plans (some members have multiple substitution plans for electroplating). The percentage value shown on each of the green bars indicates the proportion of substitution plans that are expected to have reached MRL 10 by the date indicated. MRL 10 is the stage at which there is expected to be a significant reduction in Cr(VI) usage.
***Source:* RPA analysis, ADCR members**

As a result of the individual members' substitution plans summarised above, the ADCR requests a Review Period of 12 years for the use of Cr(VI) in electroplating.

6.3 Comparison of the benefits and risk

Table 6-1 summarises the socio-economic benefits of the continued use of chromium trioxide for electroplating by companies in the aerospace and defence sector. Overall, net benefits of between ca. €4 to 7 billion for the EEA and €1 to 2 billion for the UK (Net Present Value social costs over two years/risks over 12 years, 4% discount) can be estimated for the continued use scenario. These figures capture continued profits to the applicants, continued profits to A&D companies and the social costs of unemployment. They also include the monetised value of the residual risks to workers and humans via the environment (estimated at €4.5 million and €1.7 million for the EEA and UK respectively over 12 years).

As can be seen from **Table 6-1**, the ratio of societal costs to the monetised value of the residual health risks is greater than 1000 to 1 under lower bound assumptions on profit losses and greater than 2,000 to 1 under the upper bound assumptions.

Table 6-1: Summary of societal costs and residual risks (NPV costs over 2 years/risks 12 years, 4%)

Societal costs of non-use		Risks of continued use	
Monetised profit losses to applicants	Losses in profits from reduced sales of the chromate substances and associated formulations. Losses quantified in the Formulation SEA	Health risks to workers at formulation sites over the review period, taking into account the reduction in risks due to adherence to the conditions placed on the initial authorisations. These risks are quantified and monetised in the Formulation SEA	
Monetised profit losses to A&D companies	EEA: €1,340 – 4,390 million (£1,149 – 3,777 million) UK: €340– 1,380 million (£294 – 1,187 million)	Monetised excess risks to directly and indirectly exposed workers	EEA: €1.3 million (£1.2 million) UK: €0.3 million (£0.2 million)
Social costs of unemployment	EEA: €2,800 million (£2,427 million) UK: €760 million (£656 million)	Monetised excess risks to the general population	EEA: €2.2 million (£1.8 million) UK: €1 million (£0.8 million)
Qualitatively assessed impacts	Wider economic impacts on civil aviation, impacts on cargo and passengers. Impacts on armed forces including military mission readiness. Impacts on R&D and technical innovation. Impacts from increased CO_2 emissions due to MRO activities moving out of the EEA/UK; premature redundancy of equipment leading to increased materials use.		
Summary of societal costs of non-use versus risks of continued use	- NPV (2 years societal costs/12 years excess health risks): ○ EEA: €4,154 – 7,210 million (£3,573 – 6,201 million) ○ UK: €1,104 – 2,142 million (£950 – 1,842 million) - Ratio of annualised societal costs to risks: ○ EEA: 2,649 : 1 to 4,674 : 1 ○ UK: 1,958 : 1 to 3,872 : 1		

It should be appreciated that the social costs of non-Authorisation could be much greater than the monetised values reported above, due to the likely 'knock-on' effects for other sectors of the economy:

If the Applicants are not granted an Authorisation that would allow continued sales of chromium trioxide, critical substances and formulations would be lost to aerospace and defence downstream users

↓

Due to certification and airworthiness requirements, downstream users would be forced to undertake electroplating activities outside the EEA or shift to suppliers outside of the EEA

↓

OEMs would shift most of their manufacturing activities outside the EEA/UK as it would not be technically feasible in some cases, as well as inefficient and costly, to transport parts in and out of the EEA/UK

↓

Design-to-Build suppliers may have more flexibility and shift their production activities outside the EEA, resulting in the loss of GVA and jobs to the EEA

↓

Build-to-Print suppliers in the EEA would be forced to either cease electroplating treatments or to close, where electroplating is an essential part of their production processes

↓

MROs will have to shift at least some (if not most) of their activities outside the EEA, as electroplating may be an essential part of maintenance, repairs and overhaul activities

↓

The relocation of MRO activities outside the EEA will cause significant disruption to civil aviation. This will impact on both passenger flights and cargo transport. It will also impact other aviation such as helicopters used for medical emergencies emergency

↓

Ministries of Defence will face difficult logistic difficulties with respect to the maintenance of aircraft and other equipment, with this impacting on mission readiness or the need to retire equipment prematurely. This will include the need to reach servicing agreements with non-EEA countries

↓

Passengers and freight shippers will face reduced flight availability and routes, as well as increased costs

Overall, it is clear that the benefits of the continued use of CT in electroplating activities significantly outweigh the residual risks from continued use.

Three further points are relevant. **Firstly, the use of chromium trioxide is required (and may be required beyond 12 years) to ensure the operational capabilities of the military and the ability to comply with international obligations as partner nations at the EU level and in a wider field, e.g. with NATO.**

Secondly, the requirements of the ADCR members – as downstream users - have been carefully identified and analysed, taking as the starting point the parent authorisations and the substance-use combinations covered by these. Over the lifetime of the ADCR consortium, the number of uses identified as requiring authorisation and the number of OEMs and downstream users supporting each use has decreased (including the continued need for use of the different chromate substances), to ensure that authorisation is only sought for those cases where there is no substitute that is fully qualified and certified as per stringent airworthiness requirements and industrialised by all members and within their supply chains. The continual re-visiting of supply chain requirements fed into the narrowing of the substance-use combinations requiring re-authorisation compared to the original applications for authorisation.

Finally, the non-use scenario would involve the relocation of economically and strategically important manufacturing processes. This would be in contradiction to the EU policy on "Strategic dependencies and capacities", which highlights the need to minimise such dependencies where they could have a significant impact on the EU's core interests, including the access to goods, services and technologies[87] The need to support the A&D industry (as one of the 14 priority industrial ecosystems) is explicitly recognised within the update to the 2020 New Industrial Strategy.[88]

[87] https://ec.europa.eu/info/sites/default/files/swd-strategic-dependencies-capacities_en.pdf
[88] https://op.europa.eu/en/publication-detail/-/publication/52904a0b-ae95-11eb-9767-01aa75ed71a1/language-en

6.4 Information for the length of the review period

6.4.1 Introduction

In a 2013 document, the ECHA Committees outlined the criteria and considerations which could lead to a recommendation of a long review period (12 years) [89]:

1. The applicant's investment cycle is demonstrably very long (i.e., the production is capital intensive) making it technically and economically meaningful to substitute only when a major investment or refurbishment takes place.
2. The costs of using the alternatives are very high and very unlikely to change in the next decade as technical progress (as demonstrated in the application) is unlikely to bring any change. For example, this could be the case where a substance is used in very low tonnages for an essential use and the costs for developing an alternative are not justified by the commercial value.
3. The applicant can demonstrate that research and development efforts already made, or just started, did not lead to the development of an alternative that could be available within the normal review period.
4. The possible alternatives would require specific legislative measures under the relevant legislative area in order to ensure safety of use (including acquiring the necessary certificates for using the alternative).
5. The remaining risks are low and the socio-economic benefits are high, and there is clear evidence that this situation is not likely to change in the next decade.

In the context of this review report, it is assumed that qualification and certification requirements combined with the need for approvals from EASA, the ESA and MoDs are consistent with the requirements under criterion 4 above.

Further discussion was held at the 25th Meeting of Competent Authorities for REACH and CLP (CARACAL) of 15 November 2017. A document endorsed by CARACAL suggests that, "*in order to consider a review period longer than 12 years, in addition to the criteria for a 12-year review period established in the document "Setting the review period when RAC and SEAC give opinions on an application for authorisation", two additional conditions should jointly be met*:

6. *As evaluated by the RAC, the risk assessment for the use concerned should not contain any deficiencies or significant uncertainties related to the exposure to humans (directly or via the environment) or to the emissions to the environment that would have led the RAC to recommend additional conditions for the authorisation. In the case of applications for threshold substances, the appropriateness and effectiveness of the applied risk management measures and operational conditions should clearly demonstrate that risks are adequately controlled, and that the risk characterisation ratio is below the value of one. For applications for non-threshold substances, the applied risk management measures and operational conditions should be appropriate and effective in limiting the risks and it should be clearly*

[89] https://echa.europa.eu/documents/10162/13580/seac_rac_review_period_authorisation_en.pdf/c9010a99-0baf-4975-ba41-48c85ae64861

demonstrated that the level of excess lifetime cancer risk is below $1x10^{-5}$ for workers and $1x10^{-6}$ for the general population. For substances for which the risk cannot be quantified, a review period longer than 12 years should normally not be considered, due to the uncertainties relating to the assessment of the risk.

7. *As evaluated by the SEAC, the analysis of alternatives and the third party consultation on alternatives should demonstrate without any significant uncertainties that there are no suitable alternatives for any of the utilisations under the scope of the use applied for and that it is highly unlikely that suitable alternatives will be available and can be implemented for the use concerned within a given period (that is longer than 12 years)"* (CARACAL, 2017).

As far as the second criterion above is concerned, the same document provides some relevant examples, one of which (Example (d)) reads as follows:

> "(…) *the use of the substance has been authorised in accordance with other EU legislation (e.g. marketing authorisation, certification, type-approval), the substance being specifically referred to in the authorisation/certification granted and substitution, including the time needed for modification of the authorisation/certification/type-approval, would not be feasible within 12 years and would involve costs that would jeopardise the operations with regard to the use of the substance*".

6.4.2 Criterion 1: Demonstrably Long Investment Cycle

The aerospace and defence industry is driven by long design and investment cycles, as well as very long in-service time of their products, which are always required to meet the highest possible safety standards. As noted in Section 4.4, the average life of a civil aircraft is typically 20-35 years, while military products typically last from 40 to >90 years. Furthermore, the production of one type of aircraft or piece of equipment may span more than 50 years.

These long investment cycles and long product lives have been recognised in the FWC Sector 26 study on the Competitiveness of the EU aerospace industry[90]. They are a key driver underlying the difficulties facing the sector in substituting the use of chromium trioxide in electroplating across all affected components within final products. The long service life of aircraft and other products makes it difficult to undertake all of the tests required to qualify and certify a component with the substitute, due to the level of investment and costs that would be involved in such an activity for out of production A&D products, as it would require testing at multiple levels (components, sub-assemblies, assemblies, final aircraft/defence piece of equipment).

The ADCR would like to emphasise the crucial role every single component within an A&D products plays with respect to its safety. For example, an aircraft is a complex system involving not only design of the aircraft itself, but also its use and maintenance history in varied climates and service. An aircraft engine is exposed to massive forces and extremely high stress levels due to high velocities and environmental impacts. Therefore, every single component needs to be designed and manufactured with serious attention and care.

In a complex system, change introduces new forms of failure. Any change can bring failures that can be anticipated – and some that are unanticipated. The components in an A&D product need to be

[90] Ecorys et al (2009): FWC Sector Competitiveness Studies – Competitiveness of the EU Industry with focus on Aeronautics Industry, Final Report, ENTR/06/054, DG Enterprise & Industry, European Commission.

adjusted to each other very precisely on the design as well as on the manufacturing level. When in the early design phase for completely new engines, for example, there is an opportunity to consider introducing a material change. Mostly such a material change will be a step improvement on a previous design, in line with the principle of proven engineering. Very rarely is a substantial design change introduced into an existing product, as this would involve substantial cost and risk.

Even where such a small change is considered feasible in principle, the implications are significant and highly complex; time consuming, systematic TRL-style implementation is required to minimise the impact of unanticipated failures and the serious repercussions they might cause. Even when an OEM has been able to undertake the required testing and is in the process of gaining qualifications and certifications of components with a substitute, it may take up to seven years to implement the use of a substitute across the value chain due to the scale of investment required and the need for OEMs to undertake their own qualification of different suppliers.

In addition, MoDs rarely revise specifications for older equipment, which must nevertheless be maintained and repaired. MROs servicing military equipment therefore must undertake any maintenance or repairs in line with the OEMs' original requirements. Similarly, MROs in the civil aviation field are only legally allowed to carry out maintenance and repairs in line with OEMs' requirements as set out in Maintenance Manuals. Long service lives therefore translate to on-going requirements for the use of chromium trioxide in the production of spare components and in the maintenance of those spare components and the final products and aircraft/equipment they are used in.

As such, a review period of at least 12 years is warranted and requested for the highly complex systems the ADCR is addressing in this Review Report. A 12-year review period in itself may not be sufficient for the aerospace and defence industry to fully replace chromium trioxide across all uses of electroplating, however, the industry is committed to the goal of substitution. A 12-year review period will enable the implementation of the significant (additional) investment in R&D, qualification and certification of design/drawing changes and industrialisation required across the various OEMs.

6.4.3 Criterion 2: Cost of moving to substitutes

Cr(VI) coatings were validated/certified in the 1950s and 60s and extensive in-service performance has demonstrated the performance of chromated materials. This includes modifications to design practice and material selection based upon resolution of issues noted in service. Chromate-based plating processes, due to their extensive performance history, represent the baseline that alternatives must match to demonstrate equivalence.

For example, modern commercial aircraft (including helicopters) in their entirety consist of between 500,000 to 6 million components, depending on the model. Depending on the materials of construction, 15-70% of the entire structure of an aircraft requires treatment using Cr(VI) at some point during the manufacturing process. Older models generally require a larger percentage of Cr(VI) surface treatments as the aerospace industry has worked diligently to incorporate new base materials and Cr(VI)-free protective coatings in newer models wherever it is safe to do so.

There are literally billions of flight hours' experience with components protected from wear by electroplating using chromium trioxide. Conversely, there is still limited experience with Cr(VI)-free formulations on components. It is mandatory that components coated using a Cr(VI)-free alternative are demonstrably every bit as safe as they had been when coated using a Cr(VI) product. The performance of Cr(VI)-free products can sometimes be demonstrated at the laboratory step but then fails at industrial scale, as it is impossible to replicate all in-service conditions in a laboratory. As a result, the time taken to progress through the TRL process may be increased until it is possible for the performance of the alternative to be demonstrated as per safety requirements at the aircraft level when operating under real life conditions.

Flight safety is paramount and cannot be diminished in any way. Take, for example, a compressor blade that is located in the middle of an engine. If that blade can only survive for a portion of the life of an engine because of service life (and hence maintenance requirement) limitations due to a new coating, the engine would need to be disassembled to be able to access the blades. That means taking the engine off the wing, sending it to a Repair Center, disassembling the engine and replacing the components at much shorter intervals than previously needed for the remainder of the engine. This would add inherent maintenance time and costs to the manufacturers; operators; and eventually end-use customers.

Where possible, and for specific components and final products, some new designs have been able to utilize newly developed alloys that do not require a Cr(VI)-based coating (as typically used to provide corrosion protection on metallic legacy components). However, even in newer designs there may still be a need for the use of chromate-based electroplating which cannot be replaced at present due to safety considerations.

These technical hurdles are a fundamental reason why the A&D industry requests a review period of at least 12 years.

6.4.4 Criteria 3 & 7: Results of R&D on alternatives and availability of alternatives over the longer term

Research into the substitution of the chromates has been on-going for several decades. Although use continues, it should be recognised that significant achievements have been made over this period in the substitution of the use of chromium trioxide by alternative substances or technologies. This is illustrated by the achievements of one of the OEMs in reducing by 75% (reduction by weight) of their level of dependency on use of chromium trioxide (see **Figure 6-3**).

This 75% reduction in the use of chromium trioxide by weight reflects the massive efforts and investment in R&D aimed specifically at substitution of chromium trioxide. Although these efforts have enabled substitution across a large range of components and products, this OEM will not be able to move to substitutes for chromate-based electroplating (its single most important on-going use of chromium trioxide) across all components and products for at least 12 years, and perhaps longer for those components and products which must meet military requirements (including those pertaining to UK, EEA and US equipment).

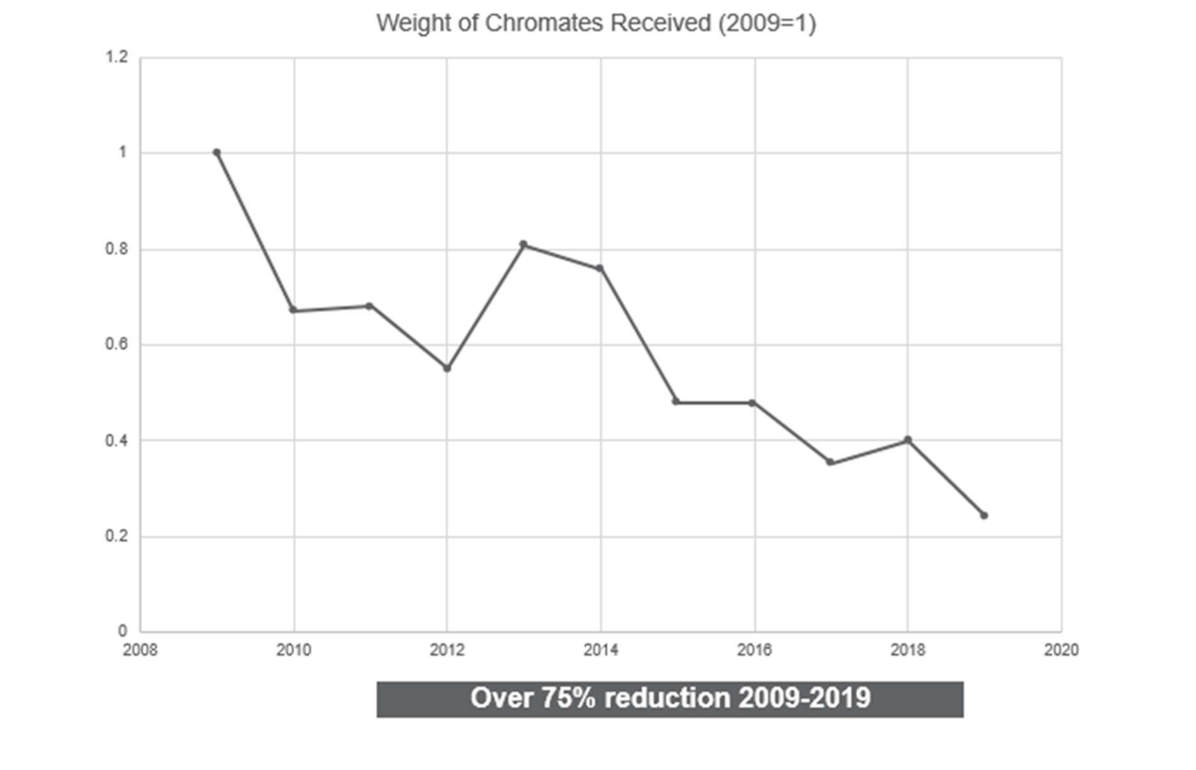

Figure 6-3: Reductions in chromate dependency over the period 2009 -2019

The European A&D industry is heavily regulated to ensure passenger/operator safety. The consequence is that there are very long lead times and testing cycles before technologies developed from a research project can be implemented into real products. Technologies which are available on the market today are the result of extensive research, including research funded by grants and conducted over the last 25+ years. In 2020, the European A&D industries spent an estimated €18 billion in Research & Development (with an approximate 40:60 split between civil and military activities, and investment in R&D in the US roughly four times higher)[91].

A PricewaterhouseCoopers (PWC) study[92] refers to the high risks of investments in the aerospace industry: "Historically, step changes have been the norm in aircraft R&D. But recent development efforts have been so expensive that it is unclear whether the companies will earn the anticipated return on their investments. Furthermore, slips in the program schedule have worsened the economics".

Corrosion prevention systems are critical to aircraft safety. Testing in environmentally relevant conditions to assure performance necessarily requires long R&D cycles for alternative corrosion prevention processes. A key factor driving long timeframes for implementation of fully qualified components using alternatives by the aerospace and defence industry is the almost unique challenge of obtaining relevant long-term corrosion performance information.

Aerospace companies cannot apply a less effective corrosion protection process as aviation substantiation procedures demand component performance using alternatives to be equal or better.

91 https://www.asd-europe.org/sites/default/files/atoms/files/ASD_Facts%26Figures_2021_.pdf

92 http://www.strategyand.pwc.com/trends/2015-aerospace-defense-trends

If such performance is not achieved, then the alternatives cannot be used. The implications for repair, replacement and overhaul must also be understood before moving to an alternative. It must be recognised that the performance delivered by one component is dependent upon the performance of other components; thus, the performance delivered by a final product is dependent upon the components used. The number of configurations of components and final products is immense, and each configuration may differ from the next in terms of its behaviour with a Cr(VI) alternative.

As noted previously, there is a complex relationship between each component and its performance requirements within its own unique design parameters, which requires component certification for each individual substitution.

6.4.5 Criterion 4: Legislative measures for alternatives

As discussed in detail in section 3.1.2, the identification of a technically feasible Cr(VI)-free formulation is only the first stage of an extensive multi-phase substitution process leading to implementation of the alternative. This process, illustrated below, requires that all components, materials and processes incorporated into an A&D system must be qualified, validated, certified and industrialised before production can commence. Each phase must be undertaken to acquire the necessary certification to comply with airworthiness and other safety-driven requirements.

From start to finish, significantly more than 12 years is required to move from Phase 1 to Phase 5 (i.e. to identify, qualify, validate, certify and industrialise alternatives) for all critical A&D applications. The ADCR OEMs and DtBs as design owners are currently working through this process with the aim of implementing chromate-free plating processes by 2036; their current substitution plans are designed to ensure they achieve TRL9 and MRL10 within the next 12 years or sooner. This includes gaining airworthiness certification or military safety approvals, both of which can take up to several years to ensure safety.

In addition, several of the ADCR members note that military procurement agencies prefer key components of defence equipment to be produced in the EEA, although there are also international agreements enabling manufacture in partner countries. In contrast to other industry sectors, shifting production to a non-EU territory and import of finished surface treated components or products into the EEA is more complex as it could create a dependence on a non-EEA supplier in a conflict situation.

They also note that the provision of defence exemptions, as allowed for in Article 2 (3) of the REACH regulation, is **not** a suitable instrument to ensure the continued availability of chromium trioxide for electroplating purposes if the renewal of the applicants' authorisations was not granted. While a national Ministry of Defence might issue a defence exemption out of its own interest, military equipment production processes can require the use of electroplating by several actors in several EU Member states (i.e. it often relies on a transnational supply chain). In contrast, defence exemptions are valid at a national level and only for the issuing Member state. Furthermore, the defence exemption process cannot be used as an alternative to the normal authorisation process unless this is necessary for confidentiality reasons and in the interest of defence. Thus, defence applications also need to be covered by the normal authorisation process.

Finally, the EEA defence sector requires only small quantities of the chromium trioxide for electroplating. On the basis of a defence exemption alone, the quantities demanded would not be sufficient for manufacturers, formulators and surface treatment companies to continue to offer their services and products. As a result, electroplating for military aircraft and equipment would not continue in the EEA or UK if other civilian applications were not also possible. This can only be ensured by the granting of an authorisation.

6.4.6 Criterion 5 & 6: Comparison of socio-economic benefits and risks to the environment and effective control of the remaining risks

As demonstrated by the information collected by the SEA questionnaire, A&D companies have invested in monitoring and the installation of additional risk management measures in response to the conditions placed on the continued use of chromium trioxide under the initial (parent) authorisations. This has resulted in reduced exposures for both workers and reduced emissions to the environment. As substitution progresses across components and products and the associated value chains, consumption of chromium trioxide will decrease and exposures and emissions will reduce further over the requested 12-year review period. As a result, the excess lifetime risks derived in the CSR for both workers and humans via the environment will decrease over the review period. These risks will also be controlled through introduction in 2017 of the binding occupational exposure limit value on worker exposures to Cr(VI) at the EU level under the Carcinogens and Mutagens Directive[93].

The European aerospace and defence industry is a world-class leader in technology and innovation. They are an essential part of the European economy contributing to job creation (880,000 direct jobs in 2020[94]) and Europe's trade balance (55% of products developed and built in the EEA are exported).

Civil aeronautics alone accounted for around €99.3 billion in revenues, with military aeronautics accounting for a further €47.4 billion in turnover; overall taking into account other defence and space turnover, the sector had revenues of around €230 billion. Of the €99.3 billion in civil aeronautics turnover, €88.3 billion represented exports from the EU.

Both acknowledged market reports of Airbus and Boeing find a growing trend in the aerospace industry. Passenger air traffic is predicted to grow at 3.6% CAGR for 2022-2041 and freight traffic to grow at 3.2% CAGR globally, according to Airbus' Global Market Forecast. By 2041, there will be some 46,900 aircraft in service, with this including an estimated 39,500 new passenger and freighter aircraft (and the retirement of some of the older aircraft. This includes delivery of new aircraft for the European market, as well as the Asian and Chinese markets in particular.[95]

Boeing's 2022 Commercial Market Outlook[96] indicates a similar level of increase, noting that the global fleet will increase by around 80% through to 2041 with the forecast value of new airplane deliveries at around US $7.2 trillion (based on a slightly higher growth in traffic at around 3.8% CAGR.

The socio-economic benefits of retaining the key manufacturing base of the EEA and UK A&D industries are clearly significant, given that they will be major beneficiaries of this growth in demand.

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93 Directive 2004/37/EC of the European Parliament and of the Council of 29 April 2004 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work (Sixth individual Directive within the meaning of Article 16(1) of Council Directive 89/391/EEC), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32004L0037

94 https://asd-europe.org/sites/default/files/atoms/files/ASD_Facts%26Figures_2021_.pdf

95 https://www.airbus.com/sites/g/files/jlcbta136/files/2022-07/GMF-Presentation-2022-2041.pdf

96 https://www.boeing.com/commercial/market/commercial-market-outlook/index.page

As demonstrated in the socio-economic analysis presented here, even without accounting for such growth in demand under the continued use scenario, the socio-economic benefits clearly outweigh the associated risks to human health at social costs to risk ratios of over 3,560 to one for the EEA and 1,426 to one for the UK.

6.5 Substitution effort taken by the applicant if an authorisation is granted

As the AoA shows, where alternatives have been proven as technically feasible – on a component-by-component basis – they have been, or are in the process of, being implemented. However, there are still many cases where components do not have technically feasible alternatives available. **Figure 3-3** highlights the actions that are being taken by A&D design owners to develop, qualify, validate, certify and industrialise alternatives for individual components.

This work will continue over the requested review period with the aim of phasing out all uses of chromate-based electroplating. As illustrated in Section 3.7, on-going substitution is expected to result in decreases in the volumes of chromium trioxide used in electroplating within the next seven years. However, technically feasible alternatives are still at the development phase (Phase 1 out of the 5 phases) for some components and final products, where alternatives have not been found to meet performance requirements.

6.6 Links to other Authorisation activities under REACH

This Review Report is one of a series of applications for the re-authorisation of the use of chromium trioxide in surface treatments carried out by the A&D industry. This series of Review Reports has adopted a narrower definition of uses original Authorised under the CTAC, CCST and GCCA parent applications for authorisation.

In total, the ADCR will be submitting 11 Review reports covering the following uses and the continued use of chromium trioxide, sodium dichromate, potassium dichromate, sodium chromate and dichromium tris(chromate):

1) Formulation
2) Pre-treatments
3) Electroplating (hard chrome plating)
4) Passivation of stainless steel
5) Anodising
6) Electroplating
7) Anodise sealing
8) Passivation of non-Al metallic coatings
9) Inorganic finish stripping
10) Chromate rinsing after phosphating
11) Slurry coatings

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8 Annex 1: Examples of standards

Table 8-1 lists examples of standards and specifications reported by ADCR members applicable to the use electroplating. The specifications/standards listed here are test methods and do not define success criteria for alternatives validation.

Table 8-1: Examples of standards applicable to electroplating/hard chrome plating		
Standard reference	**Description**	**Key function/Standard type**
SAE-AMS 2438	Plating, Chromium Thin, Hard, Dense Deposit	Industry QC spec
SAE-AMS 2460	Plating, Chromium	Industry QC spec
SAE-AMS 2403	Plating, Nickel General Purpose	Industry QC spec
AMS-QQ-N-290	Nickel Plating (Electrodeposited)	Corrosion resistance: Class 1 platings (Corrosion protective plating) shall be of the following grades: • Grade A – 0.0016 inch thick • Grade B – 0.0012 inch thick • Grade C – 0.0010 inch thick • Grade D – 0.0008 inch thick • Grade E – 0.0006 inch thick • Grade F – 0.0004 inch thick • Grade G – 0.0002 inch thick Wear resistance, abrasion resistance and corrosion protection
ASTM B568	Standard Test Method for Measurement of Coating Thickness by X-Ray Spectrometry	Layer thickness: measurement of coating thickness of metallic and some non-metallic coatings over a range of thickness from 0.01µm to 75µm.
ASTM B571	Standard Practice for Qualitative Adhesion Testing of Metallic Coatings	Wear resistance: simple, qualitative tests for evaluating adhesion of metallic coatings on various substances
ASTM B117	Standard Practice for Operating Salt Spray (Fog) Apparatus	Corrosion resistance: covers the apparatus, procedure, and conditions required to create and maintain the salt spray (fog) test environment
ASTM D1894	Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting	Tribological properties (friction): coefficients of friction related to slip properties of plastic films in packaging applications
ASTM D4060	Standard Test Method for Abrasion Resistance of Organic Coatings by the Taser Abraser	Wear resistance: a test method for evaluating abrasion resistance of coatings
ASTM D7091	Standard Practice for Non-destructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals	Layer thickness: use of magnetic and eddy gages for dry film thickness measurement

ASTM E384	Standard Test Method for Micro Indentation Hardness of Materials	Hardness: covers micro-indentation tests made with Knoop and Vickers indenters under test forces in the range $9.8x10^{-3}$ to 9.8 N (1 – 1000 gf)
ASTM F519	Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating/Coating Processes and Service Environments	Describes mechanical test methods and defines acceptance criteria for coating and plating processes that can cause hydrogen embrittlement in steels
ISO 2177	Metallic Coatings – Measurement of Coating Thickness – Coulometric Method by Anodic Dissolution	Layer thickness
ISO 2178	Non-magnetic coatings on magnetic substrates – Measurement of coating thickness – Magnetic method	Layer thickness: non-destructive measurements of thickness of non-magnetisable coatings on magnetisable base metals
ISO 3497	Metallic Coatings – Measurement of Coating Thickness – X-Ray Spectroscopic Methods	Layer thickness
ISO 4516	Metallic and Other Inorganic Coatings – Vickers and Knoop Microhardness Tests	Hardness
ISO 6507	Metallic materials – Vickers hardness test	Hardness: the Vickers hardness test is specified for lengths of indentation diagonals between 0.020 mm and 1.400 mm
ISO 9227	Corrosion tests in artificial atmospheres – Salt spray tests	Corrosion resistance: specifies apparatus, reagents and procedure for conducting neutral salt spray (NSS), acetic acid salt spray (AASS) and copper-accelerated acetic acid salt spray (CASS) tests for assessment of corrosion resistance on metallic materials, with or without permanent or temporary corrosion protection
MIL-STD-1501	Chromium plating, low embrittlement, electrodeposition	This standard covers the engineering requirements for electrodeposition of hard chromium on high strength steel substrates and the properties of deposit. Subsequent heat treating techniques needed to ensure low hydrogen embrittlement of steel are described
Source: ADCR Members		

9 Annex 2: European Aerospace Cluster Partnerships

Table 9-1: European Aerospace Clusters

Cluster Name	Country	City	Number of Companies	Employees	Sales/turnover
ACSTYRIA MOBILITÄTSCLUSTER GMBH	Austria	Styria	80	3000	650 million Euros
Aeriades	France	Grand Est	65	3100	500 million Euros 7% of total French GDP
Aerospace Cluster Sweden	Sweden	Älvängen	50		
AEROSPACE LOMBARDIA	Italy		220	16000	5.4 billion Euros
AEROSPACE VALLEY	France	Toulouse	600	147000	
Aerospace Wales Forum Limited	UK	Wales	180	23000	£6.5 billion
Andalucía Aerospace Cluster	Spain	Andalusia	37	15931	2.5 billion Euros
Aragonian Aerospace Cluster	Spain	Zaragoza	28	1000	
ASTech Paris Region	France	Paris		100000	
Auvergne-Rhône-Alpes Aerospace	France	Rhône-Alpes	350	30000	3.3 billion Euros
AVIASPACE BREMEN e.V.	Germany	Bremen	140	12000	
Aviation Valley	Poland	Rzeszow	177	32000	3 billion Euros
bavAIRia e.V.	Germany	Bavaria	550	61000	
Berlin-Brandenburg Aerospace Allianz e.V.	Germany	Berlin	100	17000	3.5 billion Euros
Czech Aerospace Cluster	Czech Republic	Moravia	53`	6000	400 million Euros
DAC Campania Aerospace District	Italy	Campania	159	12000	1.6 billion Euros
DTA Distretto Tecnologico Aerospaziale s.c.a.r.l	Italy	Apulia	13	6000	78 million Euros
Estonian Aviation Cluster (EAC)	Estonia	Tallinn	19	25000	3% of GDP
Flemish Aerospace Group	Belgium	Flanders	67	3300	1.2 billion Euros
Hamburg Aviation e.V	Germany	Hamburg	300	40000	5.18 billion Euros
HEGAN Basque Aerospace Cluster	Spain	Basque Country	56	4819	954 million Euros
Innovation & Research for Industry	Italy	Emilia Romagna	30	2000	500 million Euros

Table 9-1: European Aerospace Clusters					
Cluster Name	**Country**	**City**	**Number of Companies**	**Employees**	**Sales/turnover**
International Aviation Services Centre (IASC)Ireland	Ireland	Shannon	60	46000	3.6bn GVA
Invest Northern Ireland	Northern Ireland	Belfast	100	10000	£6.7 billion
LR BW Forum Luft- und Raumfahrt Baden-Württemberg e.V.	Germany	Baden-Wuerttemberg	93	15000	4.8 billion Euros
LRT Kompetenzzentrum Luft- und Raumfahrttechnik Sachsen/Thüringen e.V.	Germany	Dresden	160	12000	1.5 billion Euros
Madrid Cluster Aeroespacial	Spain	Madrid		32000	8 billion Euros
Midlands Aerospace Alliance	UK	Midlands	400	45000	
Netherlands Aerospace Group	Netherlands		89	17000	4.3 billion Euros
Niedercachsen Aviation	Germany	Hanover	250	30000	
Normandie AeroEspace	France	Normandy	100	20000	3 billion Euros
Northwest Aerospace Alliance	UK	Preston	220	14000	£7 billion
OPAIR	Romania			5000	150 million Euros
Portuguese Cluster for Aeronautics, Space and Defence Industries	Portugal	Évora	61	18500	172 million Euros
Safe Cluster	France		450		
Silesian Aviation Cluster	Poland	Silesian	83	20000	
Skywinn - Aerospace Cluster of Wallonia	Belgium	Wallonia	118	7000	1.65 billion euros
Swiss Aerospace Cluster	Switzerland	Zurich	150	190000	16.6 billion CHF 2.5 % of GDP
Torino Piemonte Aerospace	Italy	Turin	85	47274	14 billion euros

10 Annex 3: UK Aerospace sector

10.1Overview

10.1.1Aerospace

The annual ADS Industry Facts and Figures guide provides an indication of the UK aerospace, defence, security and space sectors' contribution to the economy in 2021, as shown in **Figure 10-1**. The Aerospace, Defence, Security and Space Group (ADS) notes that it has over 1,100+ member companies (including over 1,000 SMEs), supporting around 1,000,000 jobs (direct and indirect) across the country.

Figure 10-1: Contribution of UK aerospace, defence, security and space sectors to the economy in 2020[97]

The UK aerospace sector is considered by the government to be "hugely important to the UK economy"[98], providing direct employment of over 120,000 highly skilled jobs that pay about 40% above the national average. The sector has an annual turnover of around £77bn, half of which comes from exports to the rest of the world. It is a driver of economic growth and prosperity across the UK, given that most of the jobs (92%) are located outside London and the south east – see **Figure 10-2**.

Given the economic importance of the sector, it has been the focus of an Aerospace Sector Deal launched on 6 December 2018) under the UK Industrial Strategy. The deal is aimed at helping industry move towards greater electrification, accelerating progress towards reduced environmental impacts, and has involved significant levels of co-funding by the government (e.g. a co-funded £3.9 billion for strategic research and development activities over the period up to 2026)[99]. To date, this co-funded programme has invested £2.6 billion, across all parts of the UK.

It is anticipated that the UK aerospace sector will continue to grow into the future, due to the global demand for large passenger aircraft, as discussed further below.

97 https://www.adsgroup.org.uk/wp-content/uploads/sites/21/2022/06/ADS-FF2022-Twit-header-72.jpg
98 BEIS, Aerospace Sector Report, undated.
99 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/763781/aerospace-sector-deal-web.pdf

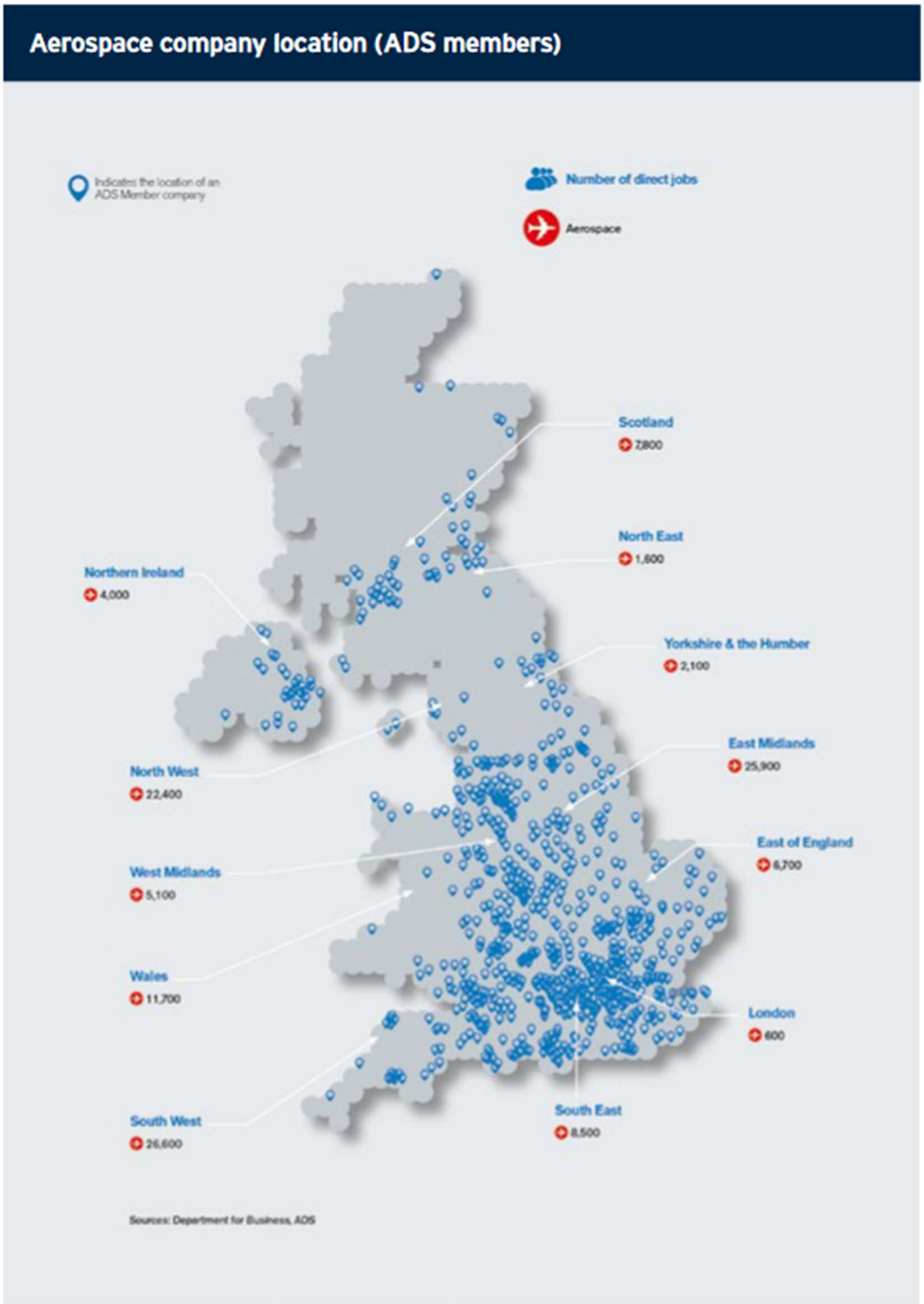

Figure 10-2: Location of aerospace manufacturing sites and associated jobs in the UK[100]

[100] Sources: ONS, BEIS, ADS Industrial Trends Survey 2020

The National Aerospace Technology Exploitation Programme was created in 2017 to provide research and technology (R&T) funding with the aim of improving the competitiveness of the UK aerospace industry, as well as other supporting measures under the Industrial Strategy. The Government's investment in R&T is through the Aerospace Technologies Institute and is programmed at £1.95 billion in expenditure between 2013-2026.

This will help in maintaining the current expected market development in the UK, which would see a 2.3% per year growth in real terms, leading to direct added value of just over £14 billion in 2035 (compared to £9 billion in 2016). In 2016, the UK aerospace sector employed around 112,500 people, with each direct job in the aerospace industry creating at least one additional job within the aerospace supply chain. This gives around 225,000 people directly and indirectly employed by the aerospace sector in high-value design and high value manufacturing jobs. By maintaining its current direction of growth, the sector is expected to create up to a further 45,000 positions by 2035.

The value of the sectors is also significant in wider economic terms. Investment in aerospace research and technology leads to wider impacts beyond the sector. Every £100 million spent on R&T by the government crowds-in around £300 million of additional private sector investment. Furthermore, every £100 million invested benefits not only UK aerospace GVA by £20 million per year, but also the wider economy by £60 million per year through technology spillovers. These include automotive, marine, oil and gas, nuclear, electronics, composites, metals and other UK industrial sectors. In total, the return on government investment in the sector is estimated as delivering an additional £57 billion of gross value added for the UK aerospace sector and a further £57 billion to the wider UK economy between 2015 and 2035.

10.1.2Defence

With respect to defence, the UK is the second largest defence exporter in the world, with its contribution to employment, turnover, and exports illustrated in **Figure 10-3**[101]. Again the importance of the sector to UK exports and value added, as well as employment is clear from **Figure 10-3**.

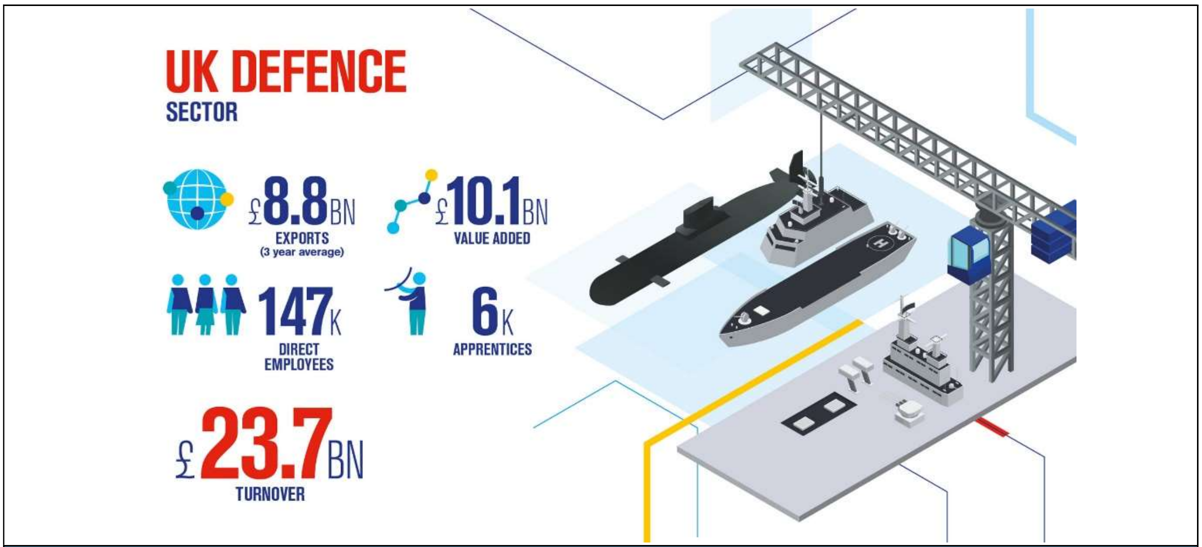

Figure 10-3: UK defence sector contribution to the economy in 2021

> 15 years

101 Sources: https://www.adsgroup.org.uk/industry-issues/facts-figures/facts-figures-2022/

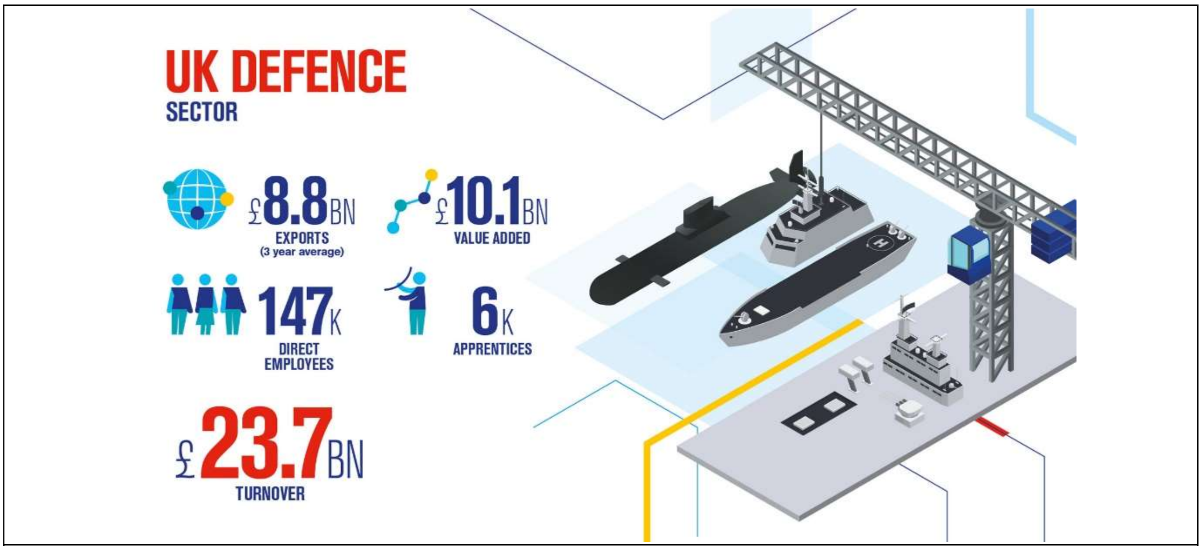

Figure 10-3: UK defence sector contribution to the economy in 2021