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Overview on the Brazilian scenario and the first efforts towards the development of a borehole repository

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ABSTRACT

The use of nuclear technologies has increased worldwide, leading to a continuous rise in radioactive waste generation. In Brazil, the National Nuclear Energy Commission (CNEN) faces growing challenges related to the safe management and disposal of radioactive waste from energy production, industrial, medical, security, and research activities. Because some waste remains hazardous for thousands of years, developing disposal solutions that protect both the environment and human health is essential. Current efforts focus on designing facilities suitable for disused sealed radioactive sources, which are not fully covered by the Brazilian near-surface repository project for low- and intermediate-level waste, Centro Tecnológico Nuclear e Ambiental (CENTENA). Although CENTENA does not include deep borehole disposal, this study examines this concept as a technically feasible complementary solution for the long-term isolation of disused sealed sources. To support container material selection for such disposal systems, a comparative electrochemical evaluation of stainless steels 316L, 2304, and 2205 was conducted in saline medium, assessing their corrosion resistance under conditions relevant to deep borehole environments. The results contribute to identifying suitable materials for long-term containment applications.

Keywords: Radioactive waste; Corrosion; Borehole; Disused sealed radioactive source.

1. INTRODUCTION

The use of nuclear radiations in Brazil started in the 1920's, when ^{226}Ra sealed radioactive sources were acquired for the foundation of the Instituto do Radio (Institute of the Radium), in 1922, and used in oncology. However, the nuclear era in the country started only in the 1950's, more precisely on September 16, 1957, when the first of the four research and test reactors currently operating in the country, attained criticality for the first time. Besides, nuclear power generation only started in the 1980's and presently, two operating nuclear reactors (ANGRA 1 and ANGRA 2) are responsible for 2.69% of the national electricity production, with a third 1.3 GW-rated power plant (ANGRA 3) under construction. High-level radioactive waste (HLW) comprises highly radioactive materials, including spent nuclear fuel and waste generated from fuel reprocessing. This type of waste is characterized by high heat generation and the presence of long-lived radio nuclides, requiring isolation in deep geological repositories to ensure long-term environmental and radiological safety.

The four Brazilian, operating non-power nuclear reactors are described as follow. The IEA-R1, a pool-type reactor supplied by Babcock & Willcox in 1957, moderated and cooled with light water, with a maximum power rating of 5 MW, initially fueled with highly enriched uranium and since 1993 with low enriched uranium. It is located at the Instituto de Pesquisas Energéticas e Nucleares (IPEN), in the city of São Paulo, and is the largest and oldest research reactor in the country. The IPR-R1, a Triga Mark I research reactor, supplied by General Atomics in 1960, operates at 100 kW and is located at the Centro de Desenvolvimento da Tecnologia Nuclear (CDTN) in the city of Belo Horizonte. The Argonauta, a 1 kW research reactor designed by Argonne National Laboratory and constructed in 1965 by the Instituto de Engenharia Nuclear (IEN), in the city of Rio de Janeiro. The IPEN/MB-01, an experimental reactor with 100 watts power, known as 'zero power' or 'critical assembly', used since 1988 to study materials and nuclear characteristics of a propulsion reactor. It was designed and constructed by IPEN and the Marinha do Brazil (Brazilian Navy), thus the reactor name MB, also located in

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city of São Paulo. The fifth nuclear, non-power reactor under construction is the Brazilian Multipurpose Reactor (RMB), with an estimated power of 30 MW, is intended for research, production of radioisotopes, testing of materials and use of radiation beams.

These reactors activities are responsible for 584 MTU of spent nuclear fuel under storage in pools or dry casks today, and will have produced a projected, accumulated amount of 2854 MTU of spent nuclear fuel by 2050. Part of this inventory can be considered radioactive waste that will be disposed of definitively, and part is considered recyclable waste. This is due to the fact that the Brazilian government decided in December 2018 (Brazil, 2019, Federal Decree 9600 of December 5, 2018) on a policy of reprocessing the spent fuel from nuclear power plants in due time, aiming at using reusable material [1–3].

Another source of radioactive waste is licensed facilities that use radioisotopes. The National Nuclear Energy Commission (CNEN) was historically responsible for both regulation and operation of nuclear activities in Brazil. Currently, nuclear regulation is under the responsibility of the Brazilian National Nuclear Safety Authority (ANSN), while CNEN remains responsible for research, development, and operational activities. More than two thousand radioactive facilities where radioisotopes, radioactive sources and radiation emitting equipment are manufactured and used in medicine, industry, research and other activities, as shown in Figure 1 [1]. Most of these services generate radioactive waste for which long-term storage and disposal is necessary.

Other activities that generate large quantities of radioactive waste in Brazil are the extraction of uranium, tin, niobium, phosphate fertilizer, rare earth, oil and gas and a few others. Brazil has large deposits of monazite sand, pyrochlore, apatite, cassiterite and other minerals to which uranium and thorium are frequently associated and that consequently produces radioactive waste when processed.

The implementation of the Brazilian near-surface radioactive waste repository is a technical and legal requirement for the expansion of nuclear power generation in the country [4]. The Brazilian repository project for Low- and Intermediate-Level Radioactive Waste (LILW), known as Centro Tecnológico Nuclear e Ambiental (CENTENA), consists of a near-surface disposal facility based on a multi-barrier concept. In addition to hosting the national LILW repository, CENTENA is planned to operate as a Pesquisa, Desenvolvimento e Inovação (PD&I) center dedicated to studies, technological development, and innovation in the field of radioactive waste management [5–7].

The CENTENA facility is designed for a period of active institutional control of 300 years, as foreseen in the Brazilian regulation ANSN NN 8.02 [4]. During this period, radiological safety will be ensured through engineering and natural barriers. The repository is intended for the disposal of all low- and intermediate-level radioactive waste generated in Brazil, originating from nuclear power plants, research reactors, medical, industrial, and research applications.

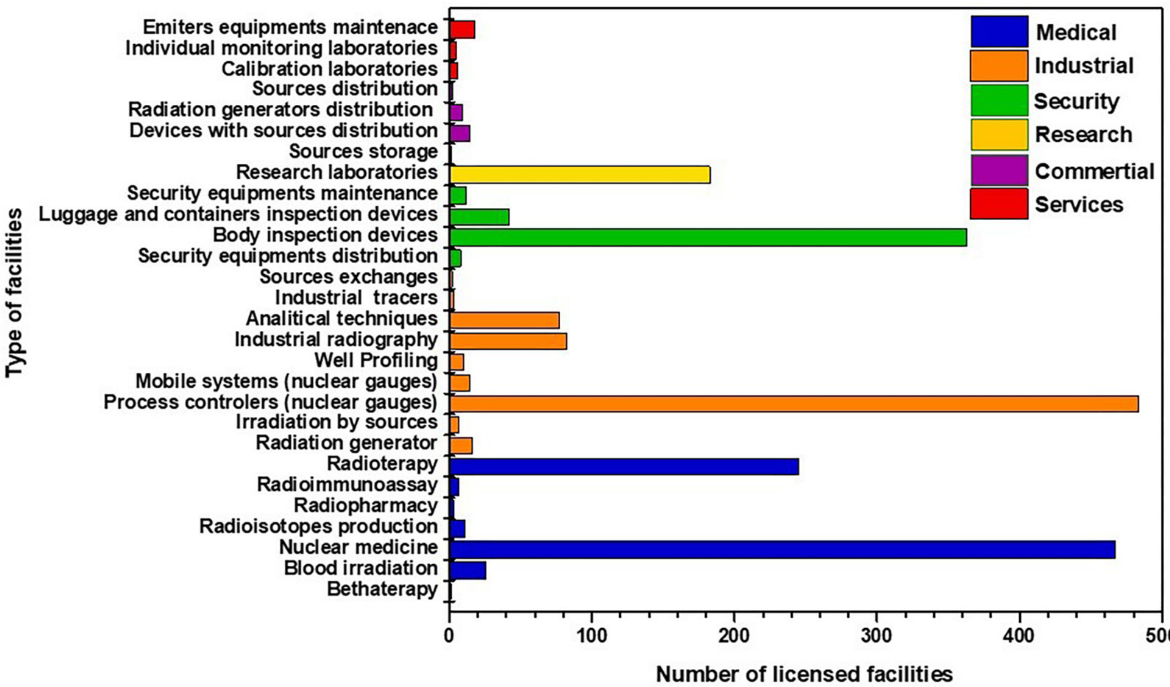

Figure 1: Number of facilities licensed to handle radioactive sources or devices in Brazil. Source: Base on [1].

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Spent Fuel from Research Reactors (SFRR) is also part of the Brazilian radioactive waste inventory; however, its final disposal is planned to occur within the CENTENA disposal area, following specific safety and conditioning requirements, and is not associated with deep geological disposal concepts. However, the Disused Sealed Radioactive Sources (DSRS) are not included in the inventory of radioactive waste that will be disposed of at the CENTENA facility [3].

DSRS do not correspond to high-level radioactive waste, as they do not include spent nuclear fuel or reprocessing waste. Instead, DSRS are typically classified as intermediate-level radioactive waste or as special radioactive waste, depending on their activity and radionuclide content. Although they are not categorized as HLW, many DSRS contain high-activity radionuclides, such as ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{241}Am, which require long-term isolation from the environment. Depending on the radionuclide and activity, isolation periods may range from several hundred to thousands of years. These characteristics impose stringent performance requirements on disposal systems and container materials, particularly with respect to corrosion resistance, mechanical integrity, and long-term containment [8].

Although the CENTENA facility is designed as a near-surface repository and does not include deep borehole disposal in its infrastructure [5], the Brazilian inventory of disused sealed radioactive sources presents specific challenges related to activity, half-life, geometry, and long-term isolation requirements. In this context, the deep borehole concept is addressed in this work as a complementary disposal solution for specific waste streams, particularly disused sealed radioactive sources, rather than as part of the CENTENA design. This approach allows the evaluation of alternative disposal strategies while remaining consistent with the national radioactive waste management framework.

The focus of this work is on the explanation of the Brazilian current scenario and, considering the IAEA-lead international effort to dispose of DSRS of many countries in a multi-barrier, deep-borehole repository concept, to select the most suitable materials for the project of a borehole disposal facility for the large inventory of the Brazilian DSRS.

1.1. Brazilian scenario

As mentioned in the Introduction, the use of nuclear radiation in Brazil started when ^{226}Ra sealed radioactive sources were acquired for the foundation of the Instituto do Radio (Institute of the Radium), in 1922, and used in oncology. Currently, the sources of radioactive waste are associated with licensed facilities controlled by the National Nuclear Energy Commission (CNEN), Figure 1.

Several consumer products that contain attached long-lived radioactive sealed sources were authorized in Brazil: these are lightning rods with ^{226}Ra or ^{241}Am, for which the license has already been revoked, surge arresters, cardiac pacemakers and smoke detectors, with the last as the only one that is still being manufactured and installed. The replacement or definitive collection of these products generates radioactive waste called generates radioactive waste called Disused Sealed Radioactive Sources (DSRS) represent a relevant fraction of the Brazilian inventory.

The implementation of the Brazilian DSRS disposal facility is still pending, as introduced above, and the focus of this work is on the explanation of the Brazilian current scenario. The wastes managed by CNEN institutions are characterized by a wide diversity in nature, forms, radionuclide contents and activities, so that, for some types of waste, specific methods of treatment and conditioning had to be developed. Some of the waste sources stored in Brazil are produced using short-lived radioisotopes in medicine and research, which can be discarded into the sewage systems after a safety decay period. However, if their activities exceed, they must be disposed in long-term radioactive waste management facilities according to the limits specified in the Brazilian regulation. The main Brazilian DSRS contains ^{241}Am, ^{60}Co, ^{137}Cs, ^{226}Ra, ^{241}Am-Be, ^{85}Kr and ^{90}Sr sources. However, ^{238}U and ^{232}Th can also be found. Usually, these spent sealed sources are dismantled to reduce their volume and conditioned [2, 3, 9]. Table 1 presents some sealed source types handled in nuclear installations in Brazil and their origin.

The Brazilian first disposal repository was projected to dispose the waste generated in the Cs-137 accident in Abadia de Goiás, in 1987. The repository is a structure built in concrete covered by layers of drainage system. The waste was packed in metallic or concrete drums, boxes or containers, depending on the volume and waste activity. Moreover, between the adjacent packages and the repository walls, the voids were filled with clay and sand material, in a proportion that allows a proper sorption of cesium ions and a good degree of compaction [3, 12–14], Figure 2.

However, despite this previous experience, the disposal infrastructure is not necessarily more complex; rather, the Brazilian waste inventory to be received contains various radionuclides with different activities and half-lives [12]. In the Abadia de Goiás repository facility only waste from the ^{137}Cs accident was disposed in;

Table 1: Main DSRS in the Brazilian inventory and their common applications. Source: Based on [3, 8, 10, 11].

ELEMENT	RADIONUCLIDE	ORIGIN
Americium	^{241}Am	Lightning rod, smoke detector, level gauge, calibration, thickness gauges, process analyzer, bone densitometry, static eliminators.
	^{241}Am-Be	Process analyzer, density gauge, moisture gauge, research reactor startup, well logging.
Cesium	^{137}Cs	Brachytherapy, calibration source, gamagraphy, process analyzer, density gauge, search, irradiators used in sterilization, irradiator for food preservation, self-shielded irradiators, blood/tissue irradiators, teletherapy, level gauges, conveyor gauges, dredger gauges, spinning pipe gauges, well logging, level gauge, moisture gauge
Cobalt	^{60}Co	Sterilization irradiators, irradiator for food preservation, self-shielded irradiators, blood/tissue irradiators, multi-beam teletherapy, process analyzer, level gauge, industrial radiography source, brachytherapy, calibration gauge, level gauge, blast furnace gauge, dredger gauge.
Iridium	^{192}Ir	Industrial radiography source, brachytherapy
Krypton	^{85}Kr	Thickness gauge
Radium	^{226}Ra	Lightning rod, moisture gauge, process analyzer, brachytherapy
	^{226}Ra-Be	Moisture gauge, calibration source, research neutron source
Strontium	^{90}Sr	Calibration source, brachytherapy, thickness gauge

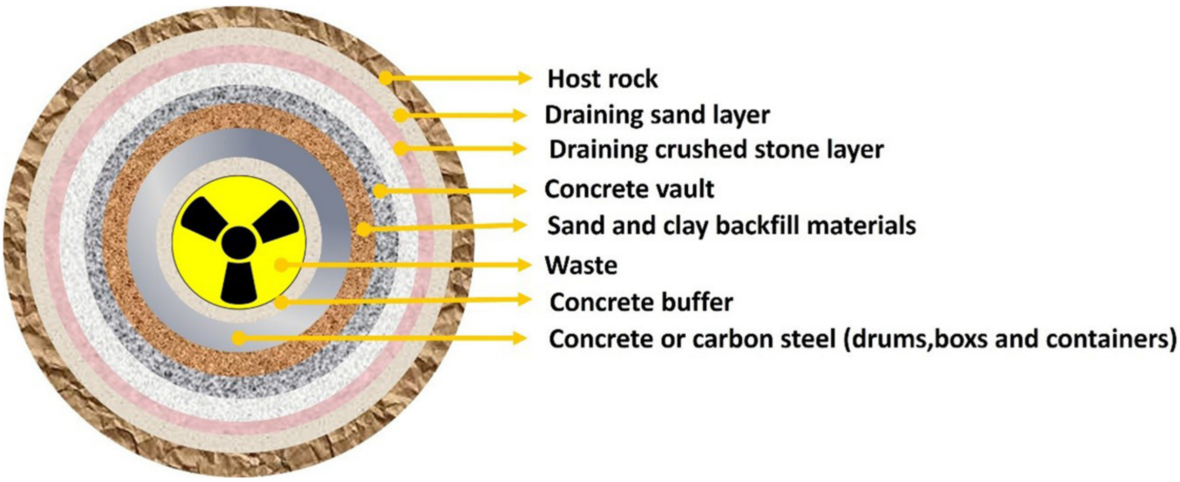

Figure 2: Schematic diagram of the Brazilian repository facility "Abadia de Goiás" showing the barrier layers composing the facility. Source: Based on [3, 12–14].

however, for CENTENA, the conditioning and safety assessment must consider the diversity of radionuclides generated in Brazilian nuclear operations.

CENTENA is the Brazilian near-surface repository facility under implementation as part of the national solution for the disposal of low- and intermediate-level radioactive waste generated in Brazil [15]. The Brazilian Repository for LILW project started in 2009. The project uses as reference the French, L'Aube ANDRA [16], and the Spanish, El Cabril Enresa [17], multi-barrier projects [7], Figure 3. In these repositories' concepts, the waste is embedded in a matrix, typically cementitious materials (e.g., concrete-based conditioning), consistent with the CENTENA concept; the use of polymeric or bituminous matrices is not foreseen for CENTENA. At the end of the operational cycle, the disposal zone is enclosed with reinforced concrete slab, covered by impermeable plastic membrane, and a final clay cap is positioned on the place. Between the disposal repository and the host rock, layers of clay and sand are used to avoid any contamination of the natural environment by radionuclides [5, 7].

CENTENA has been projected as a solution for the final disposal of radioactive waste generated in the Brazilian nuclear operations. Also, as final storage repository for LILW nuclear waste generated by the power reactors (Angra 1, 2), CNEN institutions, and the future Reator Multipropósito Brasileiro (RMB) research reactor, besides Angra 3 power reactor operations. The project is currently in its final stages. Sites of interest have been identified and the selection criterium was applied to reduce the number of candidates. The CENTENA site has been selected and is currently in the site approval and licensing phase, in accordance with the Brazilian regulatory framework [18, 19].

Boreholes are deep and narrow underground facilities for providing the level of isolation and restraint required for low volume radioactive waste. Their diameters are about dozens of centimeters, and these are directly connected to the surface during the period of operation. The depth ranges from a few dozen to a few thousand meters. They have been reported as ideal concepts for the disposal of low volumes of DSRS [8, 11]. The borehole is lined up, and the waste would normally be contained in a package with the void spaces filled with cement, Figure 4.

The function of each part of the repository, as well as the recommended material, according to IAEA is described in Table 2.

Despite the proposed IAEA borehole concept, the design of the device can change worldwide. For instance, Brazilian DSRS inventory can comprises sources of dimensions varying from few to hundreds of centimeters, Figure 5, as well as different types of radionuclides. These differences can be a limitation to the application of the IAEA proposed borehole concept.

Besides the waste dimensions, corrosion issues must be considered during the project of boreholes. For instance, the local geology can affect borehole design, as the number of barriers and the candidate materials. Few studies have been performed with candidate materials for the different barrier layers to understand their behavior in Brazilian service conditions/environments. The reports are focused on the establishment of cementation parameters for dried waste [20], characterization of clay as a backfill, coverage layers for the repository [21] and concrete as material for containers [22]. Studies on metallic packages as candidate materials to use in Brazilian environment conditions were not yet well stablished.

The Brazilian first proposal for DSRS repository has been described by VICENTE *et al.* [23], as shown in Figure 6. The structure consists of a single deep borehole penetrating in a stable geological formation with at least 4 engineering barriers: cement, steel cladding, the metallic container and the radionuclide metallic shield (generally stainless steel) and to complete the isolation the host rock will act as the natural fifth barrier. The steel jacket was projected to be a carbon steel seamless tube (ASTM A 106 as reference) with a thickness of 8.18 mm. The cement paste is pumped through the tube, filling the entire space between the tube and the host rock. The disposal zone corresponds to the place of the disposal of the metallic containers, and the rest of the borehole dimensions are the isolation zone that will be filled with concrete during the facility closure. The depths of the facility are estimated once that it is dependent on the selection of the local site geology. The deep borehole described in Figure 6 was projected for the disposal of DSRS. Therefor their dimensions comprise the use of containers stacked in a single column with the capacity of 1 L totalizing 300 containers.

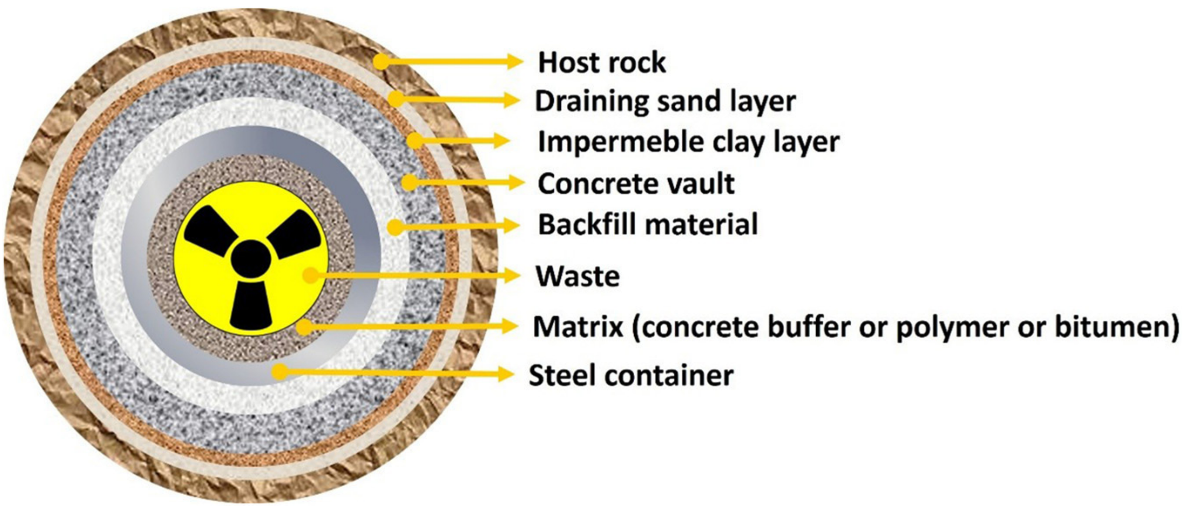

Figure 3: Schematic diagram of the multi-barrier layer of the ANDRA French program.

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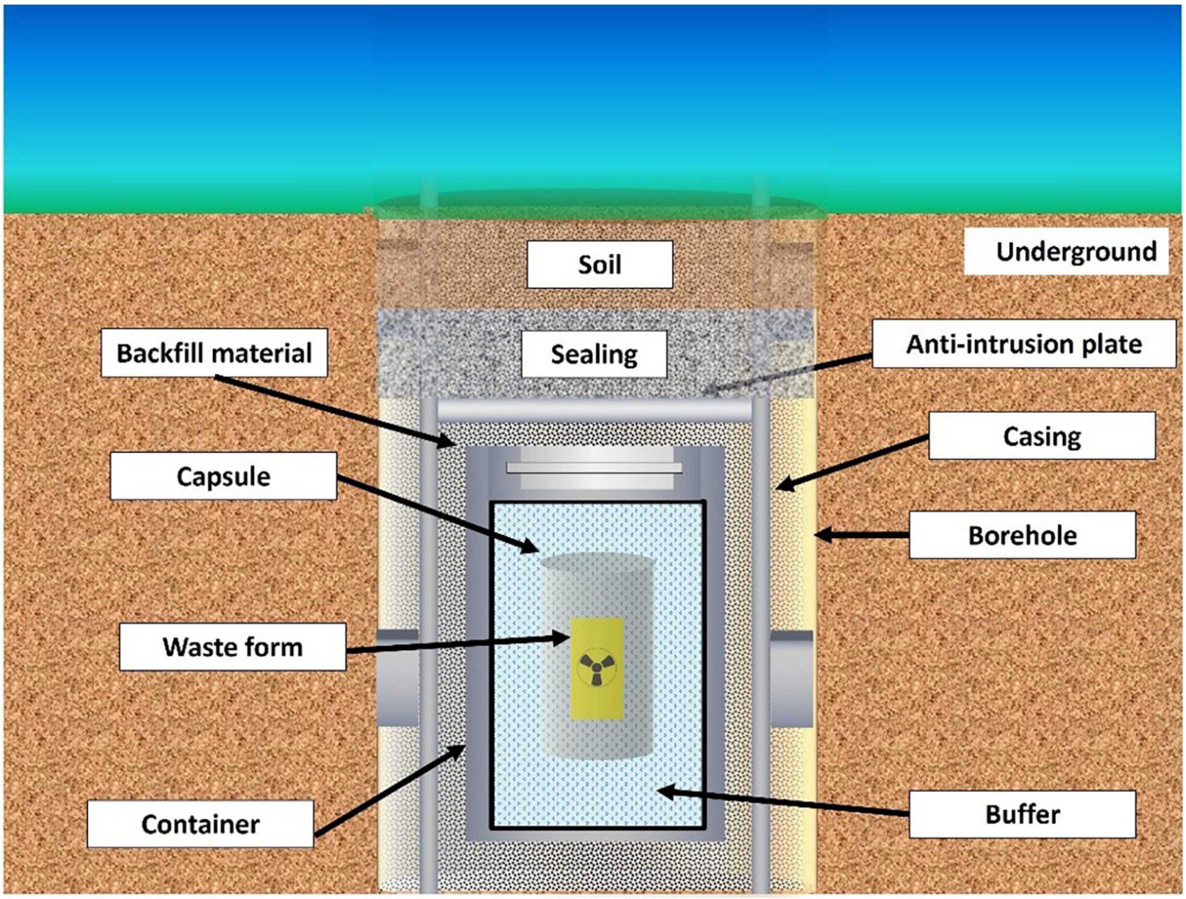

Figure 4: Borehole concept for sealed radioactive sources according to IAEA. Based on [11].

Table 2: The IAEA borehole concept description and candidate materials. Source: Based on [11].

PARTS		FUNCTION	MATERIAL
Sealing		Final device seal above the disposal zone	Concrete
Anti-intrusion plate		Prevent drilling into the borehole	Carbon steel
Casing		Assists the operations and installation steps Support the borehole wall Keeps the internal side of the device dry	Polymer (HDPE) or Carbon Steel
Backfill		Envelop the disposal package Keep the security distance between the packages Shield	Concrete
Disposal package	Container	Storage of the capsule Shield Security	316L stainless steel
	Buffer	Storage of the package Keeps the medium alkaline Shield	Pre-cast concrete
	Capsule	Storage of the waste Security Shield	316L stainless steel

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A container first concept was also proposed by VICENTE *et al.* [23], Figure 7. The structure consists of a lead body with 40 mm of thickness with a handle in steel fixed in the container body by grips of stainless steel. Despite the good corrosion properties of the steel and the good shield properties against radiation, the use of lead was not approved by IAEA, mainly due to considerations on degradation process, as corrosion. Since lead is a toxic metal, contact with groundwater can be a risk for human and environmental contamination. Besides, points of contact between the steel parts and the lead would favor galvanic couplings when exposed to corrosive environments.

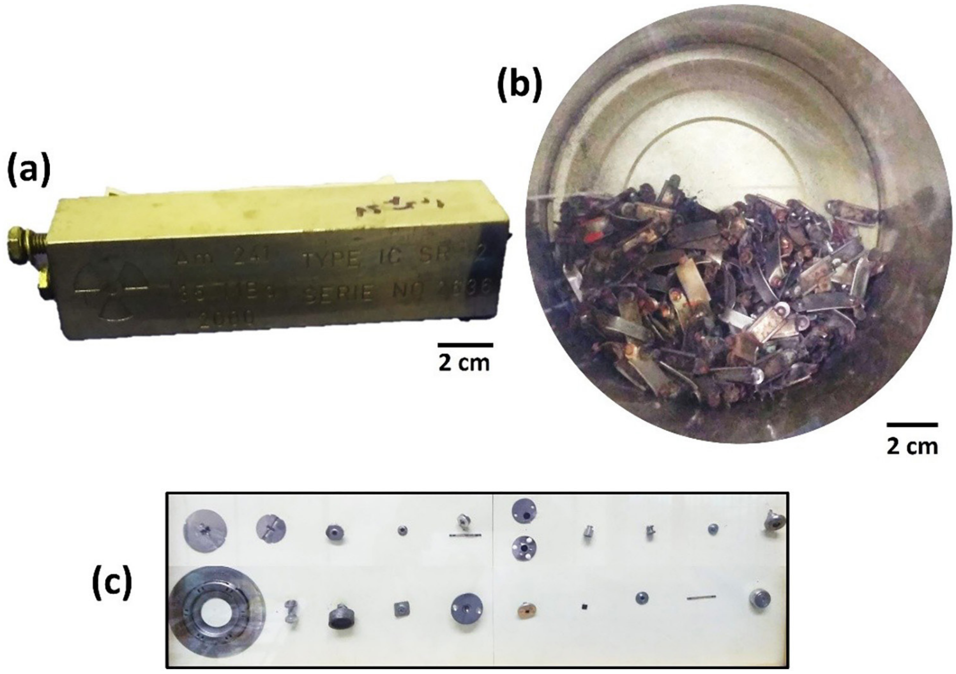

Figure 5: Examples of different sealed sources dimensions and shapes present in the Brazilian inventory. (a) Type of ^{241}Am DSRS; (b) lightning rod sources; (c) smoke detector sources. Based on [11].

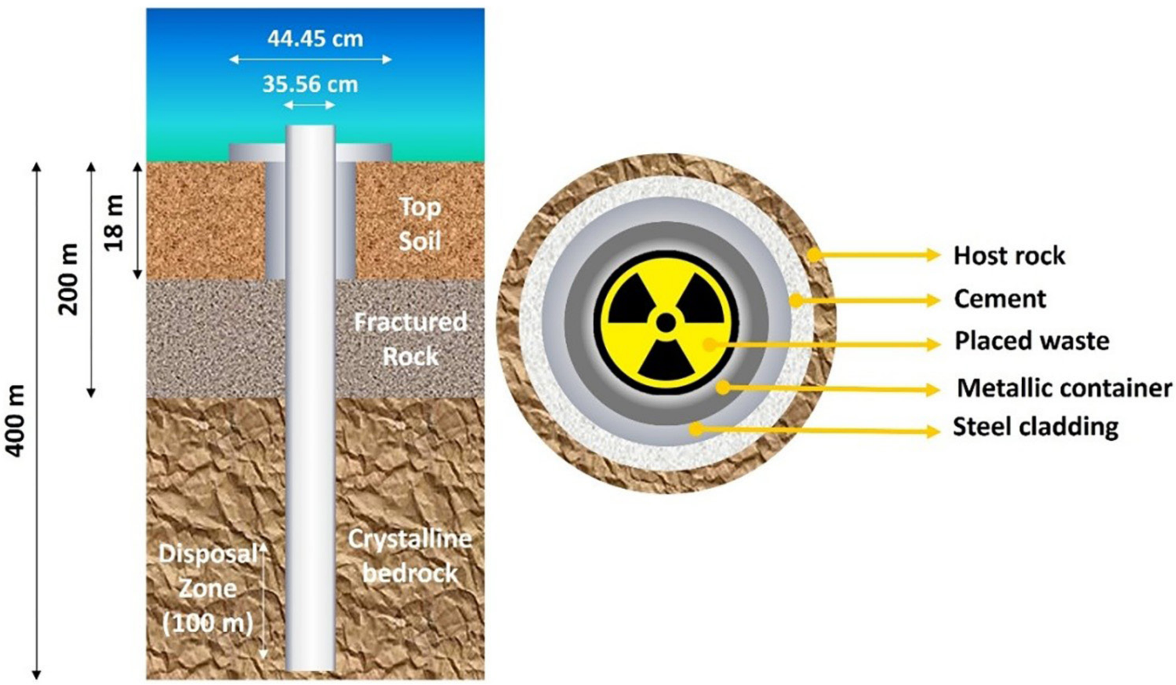

Figure 6: Schematic diagram of the Brazilian proposed borehole concept for DSRS. Based on [23].

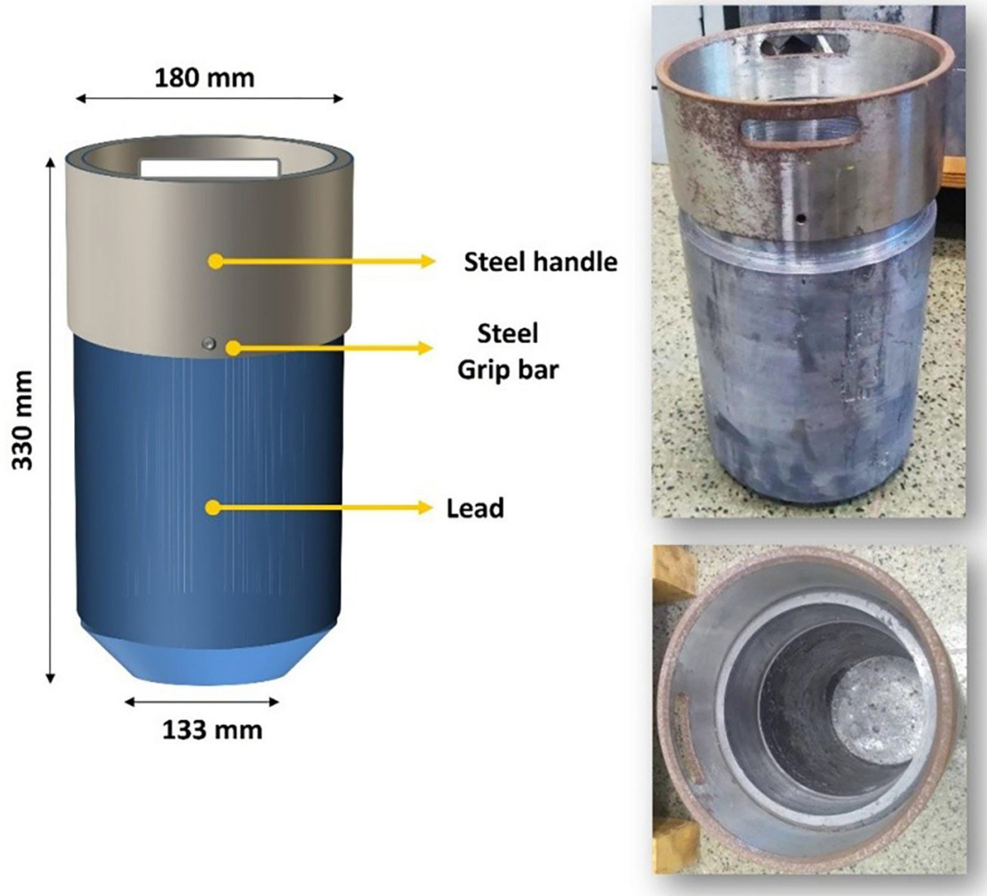

Figure 7: Brazilian proposed borehole container concept. Based on [23].

Detailed information on the CENTENA Project, including its conceptual design, regulatory framework, and site selection criteria, is available in official publications and technical reports issued by the Centro de Desenvolvimento da Tecnologia Nuclear (CDTN) and related institutional documents.

1.2. Factors that affect corrosion

Compared to other countries, the program in Brazil for radioactive waste management in deep geological boreholes is still in the very early stages. Through the support of the Canadian and U.S governments, and mainly from the IAEA, the borehole disposal facility has been in the latter stages in Ghana and Malaysia [24]. The inventory of Ghana and Malaysian consists of 256 and 12928 DSRS, respectively and the depth of their facilities can reach between (150–177) m. However, this situation is far from way of the Brazilian scenario which comprises sources from different sizes, shapes, nature and volume. It is expected for the near future a volume of about 270 000 sealed sources for final disposal [23].

Environmental geochemistry plays a crucial role in prospective studies for facility installation, since the soil and groundwater compositions affect the longevity of the device made of different materials, such as polymers, steels and concrete. The geology of Brazil is characterized by crystalline formations which cover 36% of the continental territory, and most of the rest of the continental territory is made up primarily of sedimentary basins, Figure 8. Additionally, due to Brazil territory extension, very different climatic conditions are found. At least, the territory can be divided into six different climatic conditions, and the annual rainfall may vary between regions, from more than 1000 millimeters, in the rain forest region, to few mm, in the Northeast semi-dry region.

The local site for LILW repository in Brazil has not yet been selected. The selection site must be taken into consideration the country regulations which stablish that: (a) the location must insure the retention of the waste radionuclides; (b) it must be stable in terms of geomorphology and not located in sites of seismic activities; (c) it must guarantee that radionuclides migration from the repository to groundwater be avoided or,

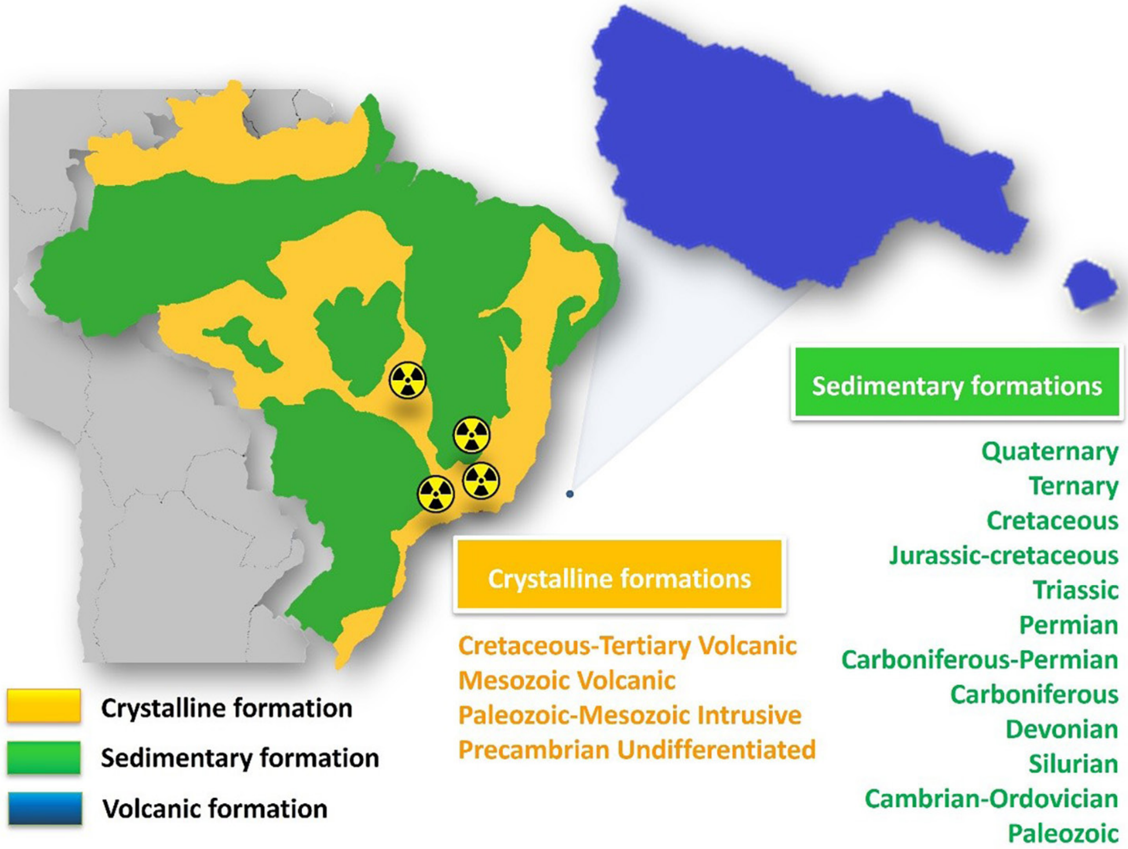

Figure 8: Brazilian geology schematic diagram. Current facilities locations with active waste repository are indicated. Based on [25].

at minimum, delayed; (d) in the last case, the water must not flow for aquifers or other public use waterways; and, (e) the radionuclides must remain for the period of decay in the groundwater in order to avoid environment contamination; (f) the facility must be built far away from the hydrological system [26].

Preliminary studies by CNEN considered the islands of Martin Vaz and Trindade as candidate sites for location of the Brazilian final nuclear LILW repository [27]. This was due to the location far from the country coast, low demography and their control by the Brazilian Navy [27]. However, since 2001, legislation has forbidden the deposition of radioactive waste in oceanic islands. Hence, other regions have been taken into consideration. For instance, regions located between the states of Rio de Janeiro and São Paulo were considered due to their strategic geographic positioning, once it corresponds to the route of the national production of materials characterized as radioactive waste of low and medium activity. A project pilot facility was proposed for experimental Borehole construction in IPEN. An important issue in the implementation of radioactive waste repositories concerns the selection and choice of a suitable site. This process involves criteria that go beyond geological aspects, including geomorphological stability, hydrogeological conditions, environmental protection, population distribution, land use, accessibility, and long-term institutional control. In Brazil, these criteria are formally established in the regulatory standard ANSN NN 6.06, which defines the technical and safety requirements for the selection and approval of sites for radioactive waste repositories. The IPEN area is located at the São Paulo Sedimentary Basin, characterized by a sedimentary formation over a crystalline basement. At the IPEN area, the sedimentary cover can reach 35–55 m in depth, and the crystalline basement is identified as granite-gneiss of Precambrian age [25].

Water radiolysis around the disposal device occurs due to waste radioactivity. As a result, a chemically reactive environment is formed, involving oxidizing species such as dissolved oxygen (O_2) and hydrogen peroxide (H_2O_2), as well as acid–base species (H_3O^+ and OH^-) and reducing species such as hydrogen (H_2). The relative importance of these species depends on the local chemical conditions, radiation field, and gas availability. If gases such as CO_2, N_2, and O_2 are present, secondary species such as CO, nitrogen oxides, nitric acid (HNO_3), and ammonia (NH_3) may be produced. For repositories in subsea formations, species such as Cl_2, Br_2, HCl, and HBr can also be formed [28]. The heat generated by waste decay may convert the humidity of the environment close to the container into steam [25, 28, 29]. In the case of borehole facilities for DSRS, the heat generated must be lower than 50 W, such that the temperature in the capsule does not exceed 50 °C. Consequently, the underground temperature and the heat generated by radioactive decay will define the temperature reached at the container/capsule surface [11]. Recently, the thermal performance of the Brazilian proposed disposal configuration (170 WP's in a single vertical borehole) was evaluated, and the temperature distribution for boreholes containing ^{60}Co- and ^{137}Cs-bearing waste packages showed a maximum temperature of approximately 66 °C at the vertical center of the borehole [30].

The backfill material used to fill and seal the borehole is a clay–cement mixture that acts as an impermeable barrier and as shielding for each disposal package. Commonly, approximately 1 m between each package is adopted for DSRS disposal; therefore, the required backfill volume depends on the disposal device design. The buffer consists of cementitious material and is used to fill the container in order to maintain a highly alkaline environment, limit oxygen diffusion, and promote low-redox conditions around the waste package, while also providing mechanical support and radiation shielding. The pre-cast concrete is made with pure water to avoid high contents of sulfides and chloride which can accelerate the corrosion process inside the package. Therefore, the corrosion behavior of package disposal can be controlled by the conditions imposed by the buffering material of the disposal site [31]. These materials have a different composition from the host rock and, thus, can alter the composition of groundwater by providing additional soluble species. Portland cement backfill has been studied as candidate material for backfill of deep borehole Brazilian project [32, 33]. The effects of irradiation on cements properties considered as candidates for the Brazilian deep borehole repository were analyzed by ALVARES *et al.* [32]. The authors observed that even lower irradiation dose than that accumulated in a waste repository of intermediate and higher level waste changes the cement matrix properties. Effects were observed on the mineralogy and microstructure, as well as an increment in the pore's sizes of the material. FERREIRA *et al.* [33] used accelerated tests and also observed effects on the cement properties. Aggressive species degraded cement pastes and mechanical strength were reduced. High temperatures increased the effect of cement compound decomposition.

In terms of corrosion resistance, austenitic stainless steels are usually selected as reference material for the DSRS disposal container due to their excellent mechanical properties and weldability. The most used grades are the 304 and 316, and low carbon equivalent grades, 304L and 316L. Despite that, stainless steels are susceptible to uniform or localized corrosion, depending on the environment [34–39]. In the United States, stainless steels were considered as candidate container materials only during the early stages of the Yucca Mountain Program. However, they were subsequently superseded by more corrosion-resistant alloys, such as nickel-based alloys, due to long-term corrosion concerns. In this context, stainless steels have been discussed primarily for hot, dry, and oxidizing environments, and mainly in relation to high-level radioactive waste (HLW) disposal concepts, rather than as a definitive container solution [40, 41].

Presently, Brazil has capability to produce 31,8 Mt y-1 of steel, being the 9th in the ranking position of steel manufacturers in the world. The consumption of stainless steel in the country is increasing each year. For instance, in 2023 stainless-steel production was about 301 thousand tons [42, 43]. They are versatile alloys which can be applied in a gamma of applications, including aggressive environments, such as oil and gas industry and pressure vessels applications.

The 2205 and 2304 duplex stainless grades are mainly applied in oil and gas industry. These steels are produced in Brazil and can be easily obtained. Their good mechanical properties and weldability make them candidates for containers for deposition of radioactive waste.

The joining of containers and capsules is a critical aspect of disposal system performance and must be carefully considered in terms of long-term integrity and corrosion resistance. In this context, welding processes are of relevance. Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) are among the most applied welding techniques for container applications, due to their technological maturity, wide industrial availability, and extensive operational experience [44–48]. These processes are well established and allow reliable control of heat input and joint quality, which is essential for stainless steel components. The materials commonly employed and the general joint configurations associated with these welding processes are summarized in Table 3.

The Brazilian DSRS inventory has particularities which make the Borehole Disposal of Sealed Sources (BOSS) concept not suitable for the Brazilian scenario. The amount, size and geometry of some DSRS founded in the Brazilian inventory make not feasible the use of individual capsules as one of the engineering barriers for the repository facility. In the absence of conventional engineered barrier systems, such as buffer and backfill materials, the primary safety function is transferred to the waste package itself, particularly the sealed source

Table 3: Summary on common joint design, material and process. Source: Based on [49].

JOINT DESIGN	MATERIAL	JOINT PROCESS
Lap or edge	Ti, Ni, stainless steel, copper	ERW, GMAW, GTAW, EBW, LAW
Square butt	Ti, Ni, stainless steel, copper	EBW, LAW, PAW
Grooves (V or U)	Ti, Ni, stainless steel, copper	GMAW, GTAW, PAW
Circumferential intersecting joint	Stainless steel	SAW

Table 4: Chemical composition of the studied materials obtained by optical emission spectroscopy with argon plasma (wt.%).

ALLOY	Cr	Ni	Mo	Mn	Si	C	Cu	P	S
2205	24,43	4.56	3,28	1,94	0,62	0,03	0,06	0,04	–
2304	23,97	3,05	0,15	1,55	0,62	0,03	0,03	0,03	–
316L	18,36	8,52	2,01	1,59	0,43	0,03	0,18	0,04	–

capsule and the external metallic container, which are expected to provide mechanical integrity, containment, and corrosion resistance over the required isolation period. Based on literature review, duplex stainless steels are considered as alternative materials for application in containers for DSRS. Their excellent corrosion resistance in aggressive environments, good mechanical properties combined with their manufacture in Brazil resulting in availability, resulted in the choice of two kinds of duplex stainless steels, specifically, the 2205 and the 2304. Characterization of the corrosion behavior of these steels (2205 and 2304 grades) was carried out and a comparison with that of the 316L steel, was carried out in this study.

In this work some well-known electrolytes as 3.5% NaCl and standard sensitization test electrolyte (2 mol L^{-1} H_2SO_4 + 0.01 mol L^{-1} KSCN) were used to perform corrosion tests to support this materials selection.

2. MATERIALS AND METHODS

2.1. Sample preparation and microstructural observation

Plates of 316L, 2304 and 2205 were obtained and their chemical composition is described in Table 4. The surfaces of the tested alloys were prepared by mechanical grinding with SiC paper (#80, #180, #320. #500, #800, #1200). After grinding, the samples were sequentially polished with alumina of 3 µm and 1 µm. The microstructure of the plates was observed by optical microscopy after etching the sample in oxalic acid 10%, 6 V for 1 min (316L) and 10% of KOH 2.5 V for 1 min (2304 and 2205).

2.2. X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) analysis was performed by using a Rigaku diffractometer with Mo-Kα radiation (λ = 0.07093 nm) using a scanning mode 2theta/theta, angular range of 7–55, step scan of 0.02, divergence slit of ½º, horizontal divergence slit of 10 mm, spreading slit of ½º, receiving slit of 0.3 mm.

2.3. Microhardness measurement

Microhardness measurements were recorded from the sample surface using a load of 50 gf for a dwell time of 10 s. A Buehler microhardness machine was employed for this purpose. 30 random measurements were recorded at the surface of each sample, and their mean values were estimated. For the dual phase materials, the measurements were performed on the austenite and ferrite phases.

2.4. Electrochemical tests

Electrochemical tests were performed in a 3.5 wt.% NaCl solution at room temperature, using a conventional three-electrode cell configuration. Although this electrolyte does not reproduce the chemical conditions expected for DSRS disposal environments, it was intentionally selected as a standardized and aggressive medium to enable a comparative evaluation of corrosion resistance among the candidate materials. Alkaline environments representative of cement–clay systems in contact with containers or capsules are acknowledged as relevant and are considered within the scope of future investigations. Potentiodynamic and cyclic polarization measurements were carried out using a Palmsens 4 potentiostat controlled by PS Trace software. All measurements were performed using a three-electrode set-up. AgCl/KCl (3 M) electrode was used as the reference electrode, a platinum wire as counter electrode, and the different steel grades as working electrode.

2.5. Cyclic and potentiodynamic polarization procedures

Cyclic Polarization tests were carried out after 15 min of immersion in 3.5% NaCl, in the anodic direction starting from OCP at a rate of 0.001 V s^{-1} until the current reached 0.001 A cm^{-2}, or until reach 2 V vs Ag/AgCl/ KCl(3 M) then reversing the scanning direction. Potentiodynamic polarization tests were carried out after 15 min of immersion. Polarization was carried out in the anodic direction starting from OCP at a rate of 0.001 V s^{-1} until the current density reached 0.001 A cm^{-2}.

2.6. DL-EPR test (Double Loop Electrochemical Potentiokinetic Reactivation)

The DL-EPR test was carried out after 30 min of immersion in 2 mol L^{-1} H_2SO_4 + 0.01 mol L^{-1} KSCN. Polarization was initially carried out in the anodic direction with scanning rate of 0.00167 V s^{-1}. The direction of polarization was reversed as the polarization reached 0.5 V vs. Ag/AgCl/ KCl (3.5M). The scan was then inverted in the cathodic direction, maintaining the same scan rate, up to the open circuit potential initially measured.

3. RESULTS AND DISCUSSIONS

3.1. Microstructural characterization

Figure 9 presents the optical microscopy of the candidate materials. The 316L is an austenitic stainless steel (ASS), whereas the 2205 and 2304 are duplex stainless steels (DSS) that present a dual phase structure. The austenite phase is not attacked, whereas the ferrite phase is the color phase.

3.2. X-ray diffraction

Figure 10 shows the XRD patterns of the candidate materials. For the 316L only austenite peaks as observed, whereas for DSS, austenite and ferrite peaks can be found. Other second phases are not visible in the XRD patterns for DSS, which indicates a low volume fraction of these phases.

3.3. Microhardness

Figure 11 shows the results of microhardness for the studied materials. It can be observed the highest hardness values were related to the 2205 alloy, suggesting improved mechanical properties of this alloy. As previously reported, due to the Brazilian inventory characteristics, encapsulation of the DSRS must be avoided, therefore the use of higher strength alloys could be interesting to maintain the integrity of the containers, since one barrier of the BOSS project was removed.

The modifications discussed for the Brazilian implementation in relation to the original IAEA BOSS concept may have important implications for long-term safety and therefore require careful consideration. In the original BOSS concept, the maintenance of a highly alkaline environment by cementitious materials is a key mechanism for reducing corrosion rates of metallic components, and the use of two metallic barriers distributes the containment and mechanical functions between the capsule and the external container. In the Brazilian context, the adoption of a cement–clay mixture may influence pH buffering capacity and chemical stability, while the use of a single metallic barrier transfers a greater safety function to the container itself. Consequently, the mechanical strength and corrosion resistance of the container material becomes even more critical to ensure long-term integrity. Although a comprehensive safety assessment of these modifications is beyond the scope of the present study, the results presented here provide relevant insights for material selection, particularly when considering the relative corrosion performance and Pitting Resistance Equivalent Number (PREN) values of the candidate stainless steels.

It should be noted that the original mill tests reports for the materials investigated were not available for this study. Therefore, microhardness measurements were employed as a comparative indicator of mechanical strength among the candidate alloys. Although hardness does not replace a full mechanical characterization, it provides useful qualitative information for comparing materials, particularly in the context of assessing container integrity when only relative mechanical performance is required.

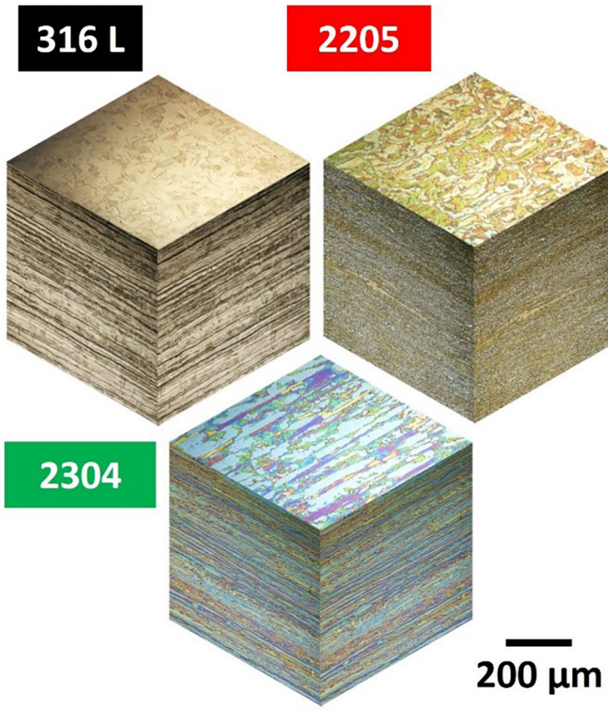

Figure 9: Optical microscopy of the candidate materials. 316L etching: 10%, 6 V for 1 min; 2304 and 2205 etching: 10% of KOH 2.5 V for 1 min.

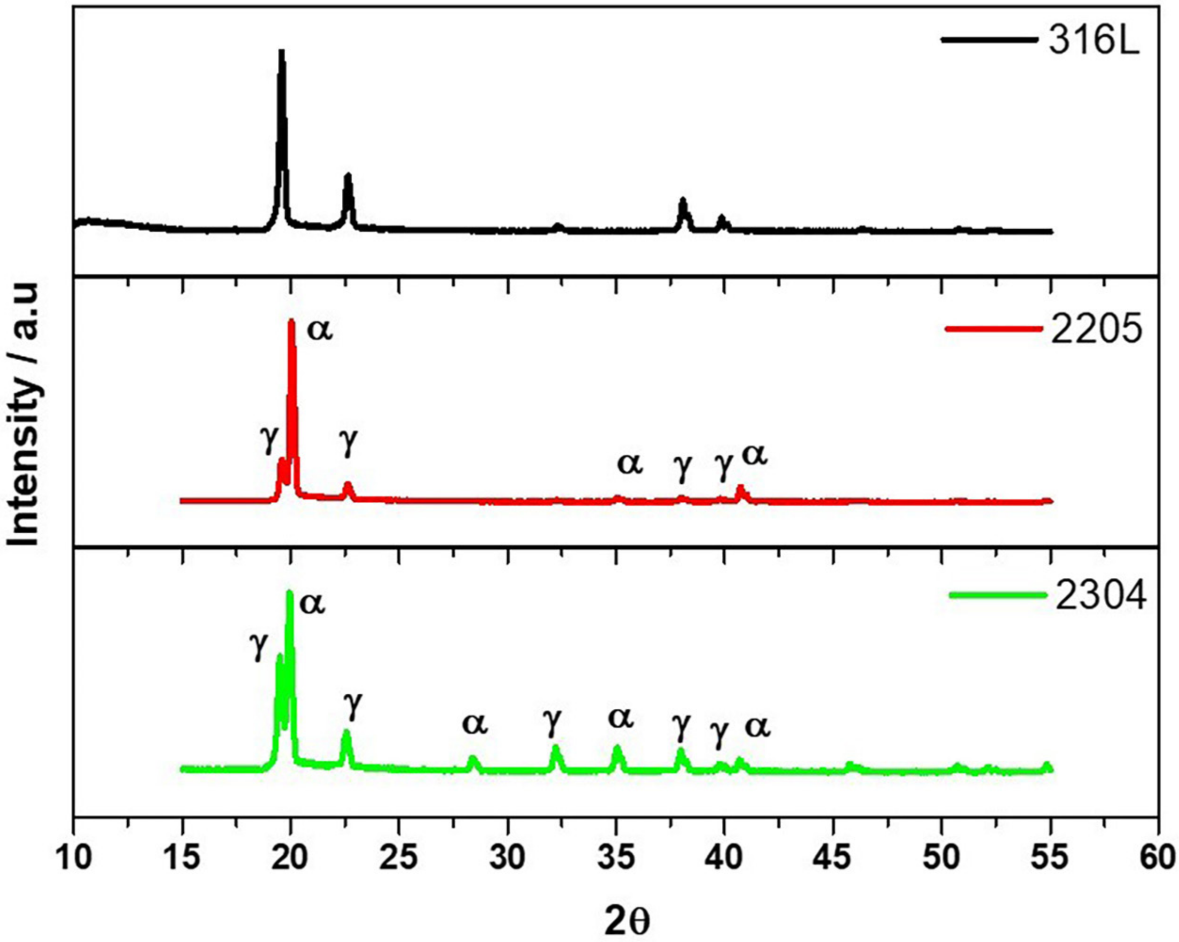

Figure 10: XRD patterns of the candidate materials. Mo-Kα radiation (λ = 0.07093 nm).

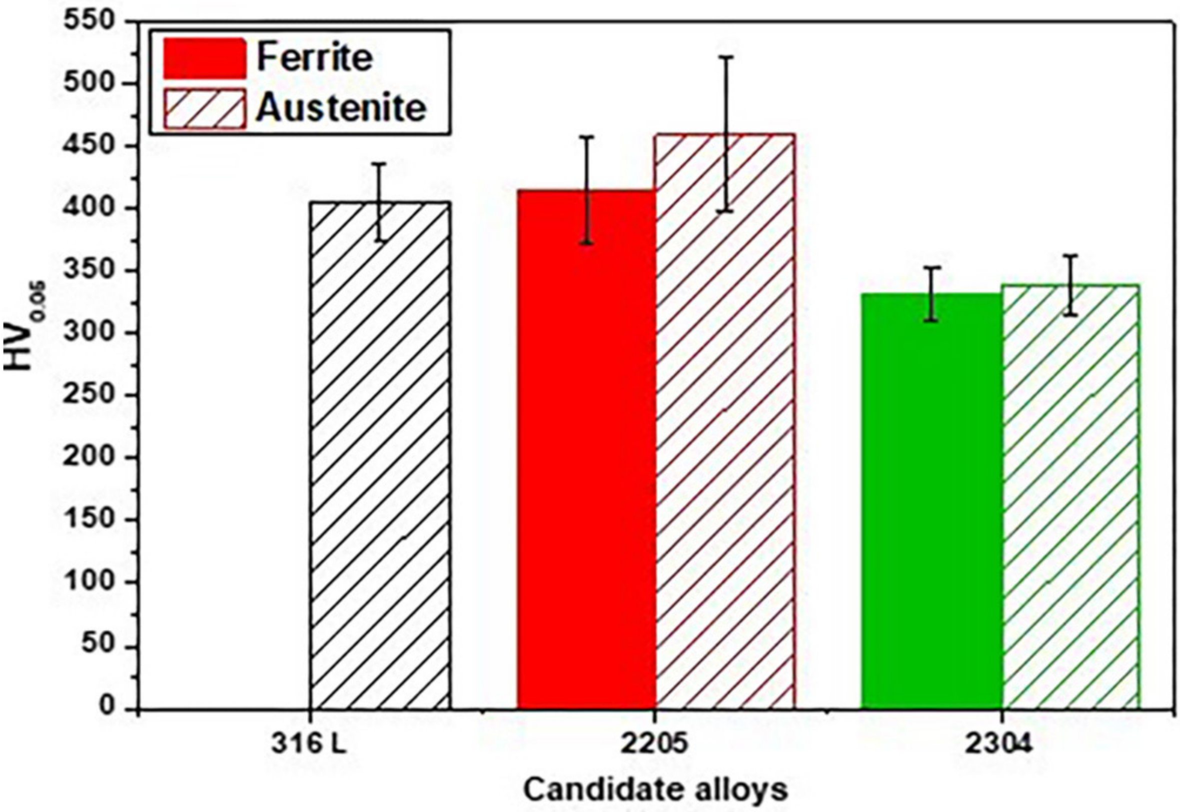

Figure 11: Microhardness average values of the studied materials.

3.4. Electrochemical characterization

The corrosion resistance of the candidate materials was evaluated at 3.5 wt.% NaCl. Cyclic polarization tests, Figure 12, showed that the smallest hysteresis area was associated with the 2205 alloy. These results indicate that this alloy has the highest corrosion resistance among the tested alloys in this type of environment.

Figure 13 supported the previous result. Potentiodynamic curves for each alloy in 3.5% NaCl showed defined pit potentials for the 316L and 2304 steels, whereas oxygen evolution was responsible for the current increment in the 2205 alloy as shown by the exposed surface micrographs, where no pitting was observed for this condition.

The apparent difference in the electrochemical response of the 2304 alloy between cyclic polarization (Figure 12) and potentiodynamic polarization tests (Figure 13) can be explained by the distinct sensitivities of these techniques. While cyclic polarization provides information on the overall stability and repassivation ability of the passive film, potentiodynamic polarization is more sensitive to localized film breakdown. The relatively similar behavior of 2304 and 2205 in the cyclic polarization curves is attributed to the high chromium content of 2304, which promotes initial passive film formation. However, the absence of molybdenum in 2304 results in lower resistance to pit initiation and propagation, leading to a defined breakdown potential like that observed for 316L. In contrast, the combined presence of chromium, molybdenum, and nitrogen in 2205 stabilizes the passive film and suppresses localized corrosion under the tested conditions.

The exposed surface of the 2304 alloy was attacked after the test, Figure 14. Pits mouth was observed to spread over both austenite and ferrite. However, smaller pits were observed to be in the ferrite.

Results of the Double-loop Electrochemical Potentiodynamic Reactivation tests performed in 2 mol L^{-1} H_2SO_4 and 0.01 mol L^{-1} KSCN to evaluate the susceptibility of the alloys to intergranular corrosion are shown in Figure 15.

The presence of a small reactivation current peak for the 2304 alloy (Figure 15 (b)), which is absent for the other alloys, suggests a limited degree of electrochemical reactivation. However, because replicate measurements were not performed, this observation is interpreted qualitatively rather than as a definitive quantitative ranking of sensitization susceptibility [50]. The low reactivation response observed for 2304 is nevertheless consistent with the well-established behavior of duplex stainless steels, which are generally less

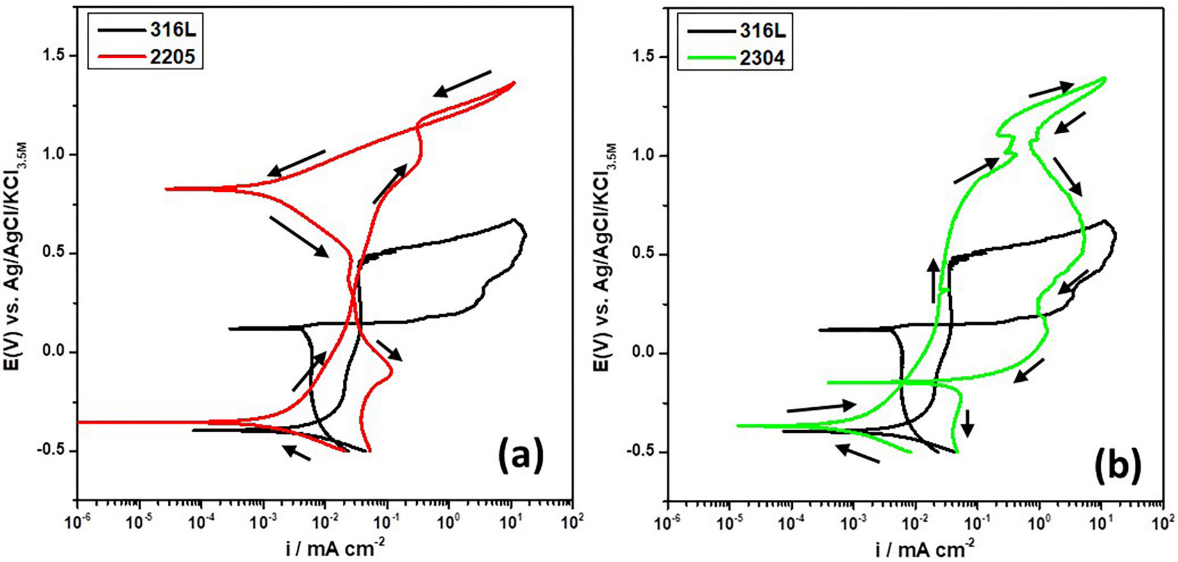

Figure 12: (a), (b) Comparison of the cyclic polarization curves of the 2205 and 2304, respectively, with the 316L after 15 min of immersion in 3.5% NaCl. Arrows indicate the direction of polarization.

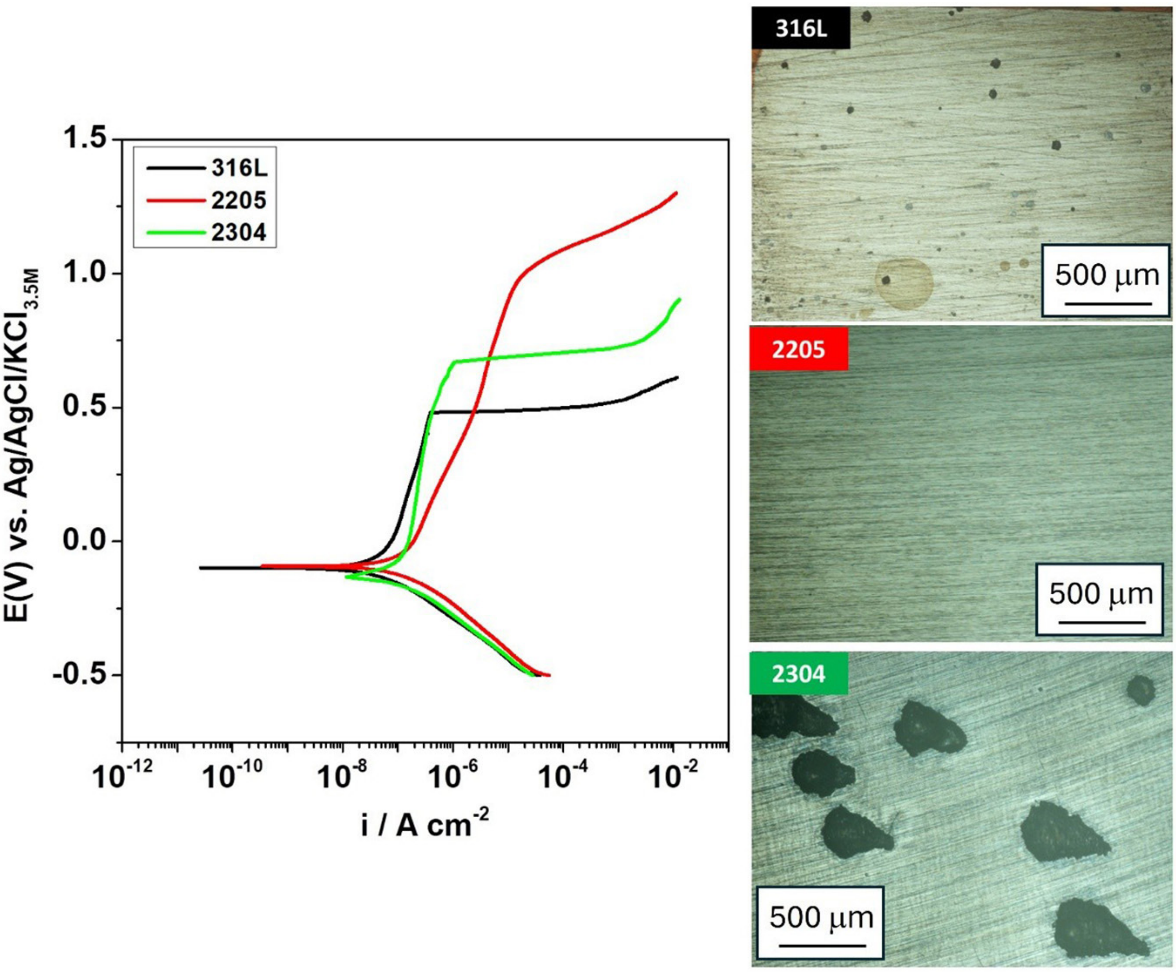

Figure 13: (a), (b) Comparison of the potentiodynamic polarization curves of the 2205 and 2304, respectively, with the 316L after 15 min of immersion in 3.5% NaCl.

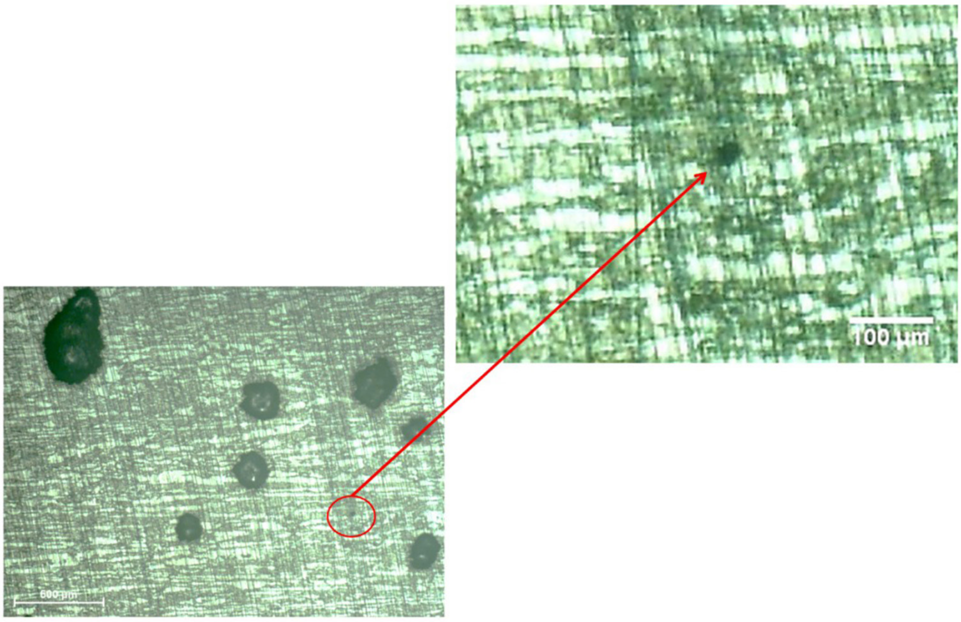

Figure 14: Optical micrographs of the 2304 alloy exposed surface after anodic polarization in 3.5% NaCl etched with Behara.

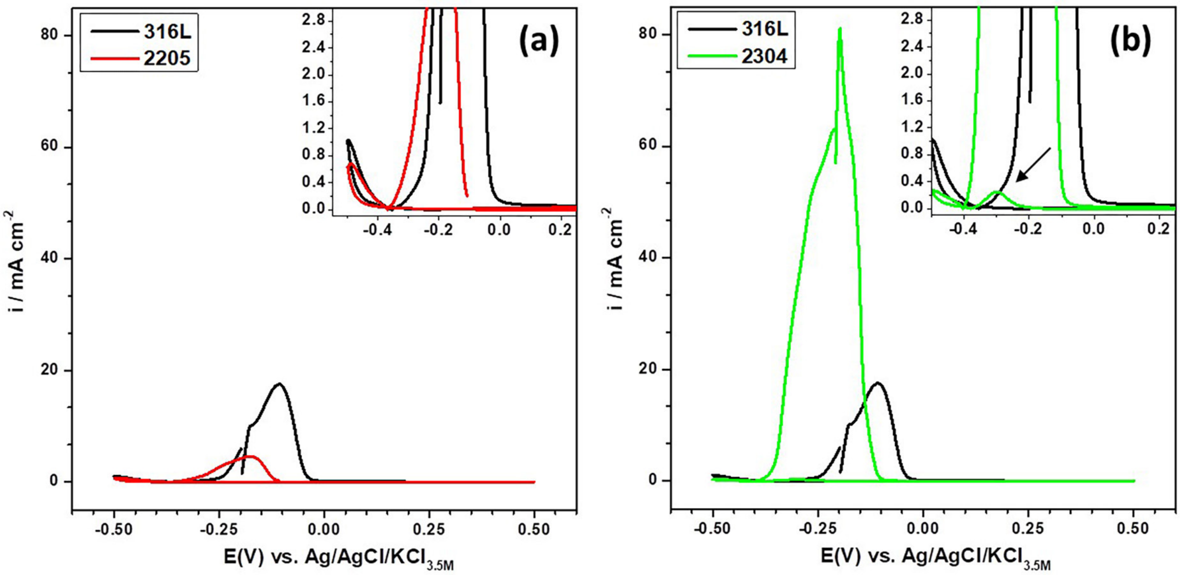

Figure 15: Comparison of DL-EPR curves for the (a) 2205 and 316L stainless steels and (b) 2304 and 316L stainless steels. The black arrow in (b) indicates a reactivation current peak for the 2304 alloy.

susceptible to sensitization than fully austenitic grades [51]. This is attributed to the dual-phase microstructure (austenite/ferrite), where chromium diffusion is faster in the ferritic phase, promoting more rapid restoration of chromium-depleted regions at austenite/ferrite boundaries and reducing the extent of sensitization [52]. In this context, the DL-EPR results indicate that 2205 exhibits the highest resistance to intergranular attack among the alloys studied (Figure 16), while 2304 shows a minor reactivation feature under the present testing conditions [50, 51].

In neutral media, 3.5 wt.% NaCl the 316L and 2304 candidate materials showed higher susceptibility to localized corrosion than the 2205 alloy. In this condition pits are reported to appear in the ferrite, as observed in Figure 14, for the 2304 alloy. On the other hand, pits were not observed in the 2205 alloy. For this alloy, the

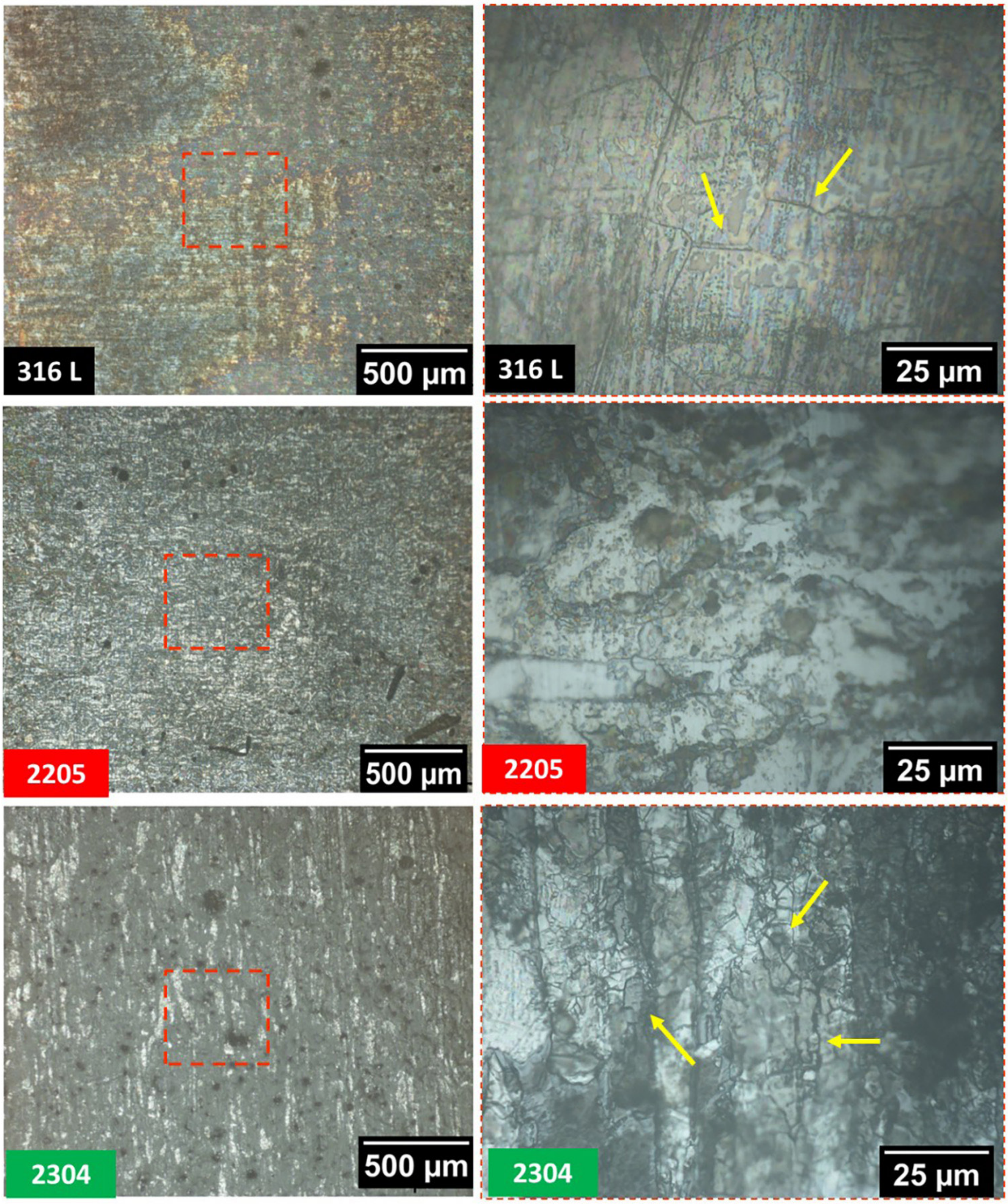

Figure 16: Optical microscopy of the exposed surfaces of the candidate materials after DL-EPR test. The yellow arrows indicate intergranular corrosion.

increase in current at potentials above 1.0 V are due to the oxygen evolution reaction. The difference between 2205 and 2304 electrochemical response can be related to their differences in Cr and Mo content. Mo is a ferritizer element and tends to be localized in the ferrite. The lower Mo content of 2304 explains why ferrite corrodes preferentially during the tests, while the 2205 is more resistant. In the case of the differences in the corrosion resistance of the 316L and 2205 alloy, it can be related to the lower Cr and Mo content in the 316L. Cr is the element mainly responsible for the enhanced corrosion resistance of stainless steels. This is supported by the DL-EPR results, where chromium-depleted or sensitized regions, are present in the 2304 and 316L. Additionally the ferrite grains etching also indicates the lower corrosion resistance of this phase in the duplex stainless steel than the austenite one.

4. CONCLUSIONS

This work is part of a Brazilian study on the proposal of a disused sealed sources disposal facility due the specificity of the Brazilian inventory alternative materials is proposed in relation to the reference material indicated by the International Agency Atomic Energy Agence (IAEA). As the great volume of the Brazilian nuclear waste are composed of LILW and the encapsulation of the DSRS are not suitable, metallic materials as duplex stainless steels are shown to be suitable for containers applications. Corrosion tests at room temperature were performed to compare the corrosion resistance of the candidate materials 2304 and 2205 duplex stainless steel with reference material 316L austenitic stainless steel. The preliminary results showed that the 2205 is a potential candidate for replace the 316L based on its corrosion behavior in higher chloride electrolytes and better mechanical resistance. On the other hand, the 2304 showed lower localized corrosion resistance and susceptibility to intergranular corrosion. Beyond the assessment of corrosion-resistant materials for repository applications, this study contributes to the broader discussion on radioactive waste disposal strategies in Brazil. While CENTENA provides a national solution for low- and intermediate-level radioactive waste through a near-surface repository, the results presented here support the deep borehole concept as a technically feasible complementary option for specific waste inventories, particularly disused sealed radioactive sources. Future work should focus on site-specific assessments, long-term performance of engineered barriers, and corrosion behavior under repository-relevant environmental conditions.

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