Safety and Performance by Design

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Abstract

New and advanced designs of gamma radiography exposure devices and sources have been developed by SENTINEL™ with the aim of exceeding today's high safety and performance standards in anticipation of the future needs of the Industry for continual improvement. The importance of safety combined with high performance and good value is paramount in the Gamma Radiography Industry. Product safety and performance go hand in hand. They are achieved through the application of innovative design solutions within a safety-oriented design culture. This paper describes the process of developing innovative products and solutions adopted by SENTINEL. The development of the SENTINEL 880 series gamma radiography exposure device and the ***75Se**ntinel*™ gamma radiation source are described by way of example to show how safety and performance can be designed-in. The main safety and performance features are described. All new products require rigorous operational trials combined with destructive integrity tests to confirm fitness for purpose. The results of these tests are described. Products are designed to meet all of the international safety and regulatory standards throughout the world such as BSI, ISO and ANSI and to anticipate future changes in the regulations so that users can be assured products will continue to comply in the future throughout the world. Safety is enhanced through simplicity of operation and through clear procedures, which assure low operational radiation exposure during use. An important part of the design process for SENTINEL products is the participation of regulators, industry leaders and users who provide valuable input and feedback throughout the development process to ensure all aspects of the product and future needs of Industry are met.

Development of the SENTINEL Model 880 Exposure Device

Dateline: Summer 1998
The Sentinel commercial team concluded the time was right to develop a new design to replace the 30-year legacy product, the Model 660 series radiographic exposure device. A task team consisting of regulatory/health physics, operations and the business group held several detailed meetings to determine the best method to develop the new exposure device/system. An agreement on the development process was made by the SENTINEL commercial team. Sentinel was to obtain the system specifications from the industry users to ensure the system was what the industry needed. Only then could the design engineers apply the equipment standards and the regulatory overlay to the new design. The business group also wanted innovations that would incorporate increased radiological safety and meet equipment requirements over the next two decades. The business group presented the business case for the development project in which the Board of Directors approved and allocated funds.

Dateline: Fall 1998 - Assessment phase 1
An industry focus group consisting of Radiation Protection Officers and the Senior Management of large-scale non-destructive testing laboratories provided their opinions and input during the Fall ASNT conference held in Seattle, Washington. The information provided by the focus group spearheaded the design specifications. A question was presented to the focus group. “If Sentinel could wave a magic wand that could create the ideal exposure device, what would it look like?” The focus group described their ideas in such detail, drawings were needed to ensure their ideas were understood. Valuable insights were provided by simply asking the questions, listening and asking for clarifications as needed. Their input was based on actual usage in a wide range of environmental conditions, the radiological safety of the exposure devices, equipment ergonomics to increase safety, transport safety, the ease, cost and downtime for routine maintenance. Past accidents and the good and bad attributes of all devices available commercially were presented by the group. The basic shape, specific requirements, maximum weight, protection, center of gravity, serviceability, function, type of shielding configuration, radiological safety, the ability to use multiple isotopes and expected working life of the exposure device were clearly defined.

Dateline: Spring 1999 - Assessment phase 2

The commercial task team expands focus group meetings with NDT companies throughout the world. Additional information and new concepts are discussed with the focus groups on the "ideal" exposure device. The new concepts that were introduced required the new design to permit use as a conventional crank-out system. The new design needed to provide utility for use on gas-pipeline sleds or to be used on an isotope crawler-head (category X device). Additional feedback was compiled on the pros and cons of all commercially available radiography systems. Cost, weight, durability, reliability, versatility and intrinsic radiological safety and designed ergonomics became the universal input provided by the five additional focus groups.

Additional information was gathered from interviews with radiographers at job sites. They provided quality information from a user's perspective and really knew what they wanted in a newly designed projector. Lower weight, ease of set-up and disassembly of the system, transport, handling comfort, shape and stability on work surfaces, dose-rates and durability in the field were the most commonly cited attributes the new system should incorporate.

The Sentinel quality assurance, regulatory department, engineering and service departments provided the additional insight by providing trends they had identified through routine contact with the customer base.

Dateline: Summer 1999 - The first project review meeting

The initial assessment was completed. Technical specifications were created for the new design based on the industry input, using current and future issues of the ISO and ANSI standards, IAEA, USDOT, Transport Canada transportation regulations and applicable country regulations for radiography systems. This would ensure the product would comply and continue to comply with all known and anticipated international regulations throughout the world. The technical specifications were distributed to all department managers at Sentinel for their review and commitment for the endeavour under ISO9001 requirements. The engineering staff reviewed the technical specification in conjunction with all radiography equipment standards, quality and regulatory requirements and provided feedback on the preliminary design criteria. The technical specifications were revised to reflect two Category 2 devices, a pipeline version and crawler-head version (category X). Scheduling companies for field trails was started six months in advance requiring regulatory and technical staff to send submissions to government agencies and create operating manuals. Concept drawings were presented at one of the now weekly and fully staffed project meetings.

Dateline: Fall 1999 - Concept design

The engineers created a cad-model of the new device that would be used for building the prototype unit and subjected to the "chicken test" on software animated crash programs. The test refers to (jet engine) engineers who throw whole frozen chickens into a jet engine running at full throttle to simulate the adverse conditions they may encounter during service. In most cases, the computer simulated tests are conducted before the chance of destroying an expensive, one of a kind prototype. Simulations of the 9-meter drop test produced minimal damage and plenty of bounce, which indicated the forces of the drop were not being absorbed by the device. The engineering department released drawings for the approval signoffs to build the prototype units.

Dateline: Winter 1999 - Manufacture and testing of prototypes

Prototype components were manufactured, tested and operationally tested (and abused). Progress reports by engineering staff were reported on a weekly basis. First-article inspections and process qualifications were documented throughout the manufacture of the prototype units. Two versions of the Model 880 exposure device were manufactured. The Model 880 Delta had a maximum capacity of 5.55 TBq. of ^{192}Ir with a maximum weight of 22kg. The Model 880 Elite had a maximum capacity of 1.85 TBq. with a maximum weight of 11.4kg. Physical testing of the prototype units was completed and the safety analysis reports were forwarded to the applicable regulatory agencies to obtain R&D authorizations to use the prototypes under actual field conditions. Authorizations were received in late 1999.

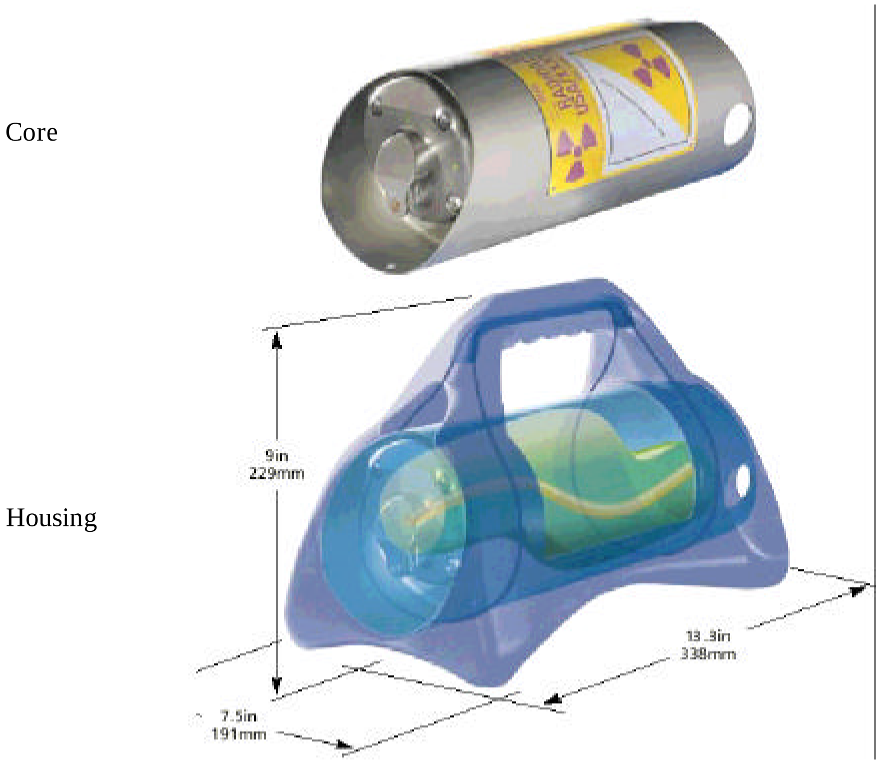
Dateline: Spring 2000 - Field trials

Field testing of the Model 880 Delta and Model 880 Elite systems started in late spring. Comprehensive daily reports were completed by the radiographers performing the field tests. A summary report was completed by the radiation protection officer of each company involved in the field trials. The daily and summary reports were submitted to the Sentinel engineers and regulatory department reviewers for input on the final design. The reports provided the confirmation that the engineers had designed a device that would meet the industry's immediate and long-term needs. The summer months of 2000 were dedicated to final testing of the system and submission for the Model 880 certifications. Manufacturing processes for production were validated.

Dateline: Fall 2000 - Authorizations
Safety analysis reports were reviewed by the State Of Massachusetts, USNRC, USDOT, CNSC. Submissions to a few other countries were also dispatched. The Sealed Source and Device Registry permitting manufacture and distribution was granted for the State of Massachusetts. The Model 880 received a transport certification from the USNRC and a Competent Authority Certification from the USDOT. Separate endorsements were issued by the Canadian Nuclear Safety Commission.

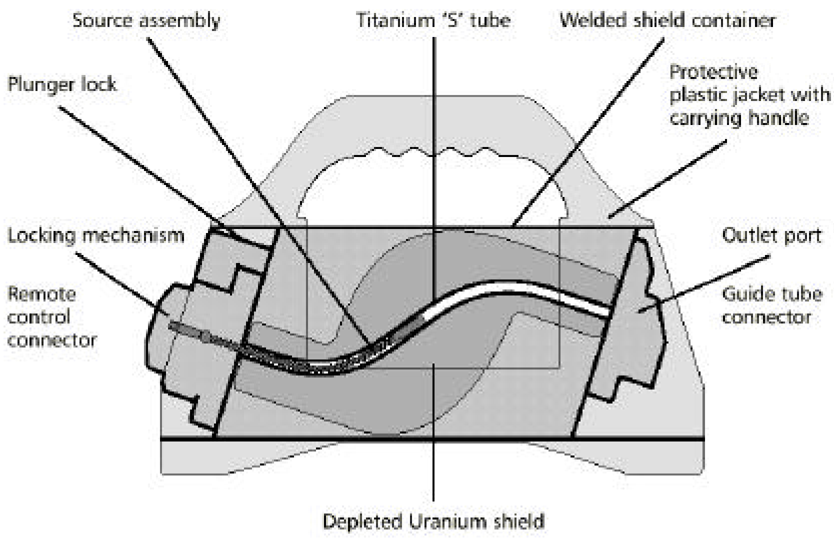
The final outcome of the project can be seen in the figures below. Figure 1 shows the general construction and design features of the device:

Figure 1 - Construction and design features of the SENTINEL Model 880 Exposure Device



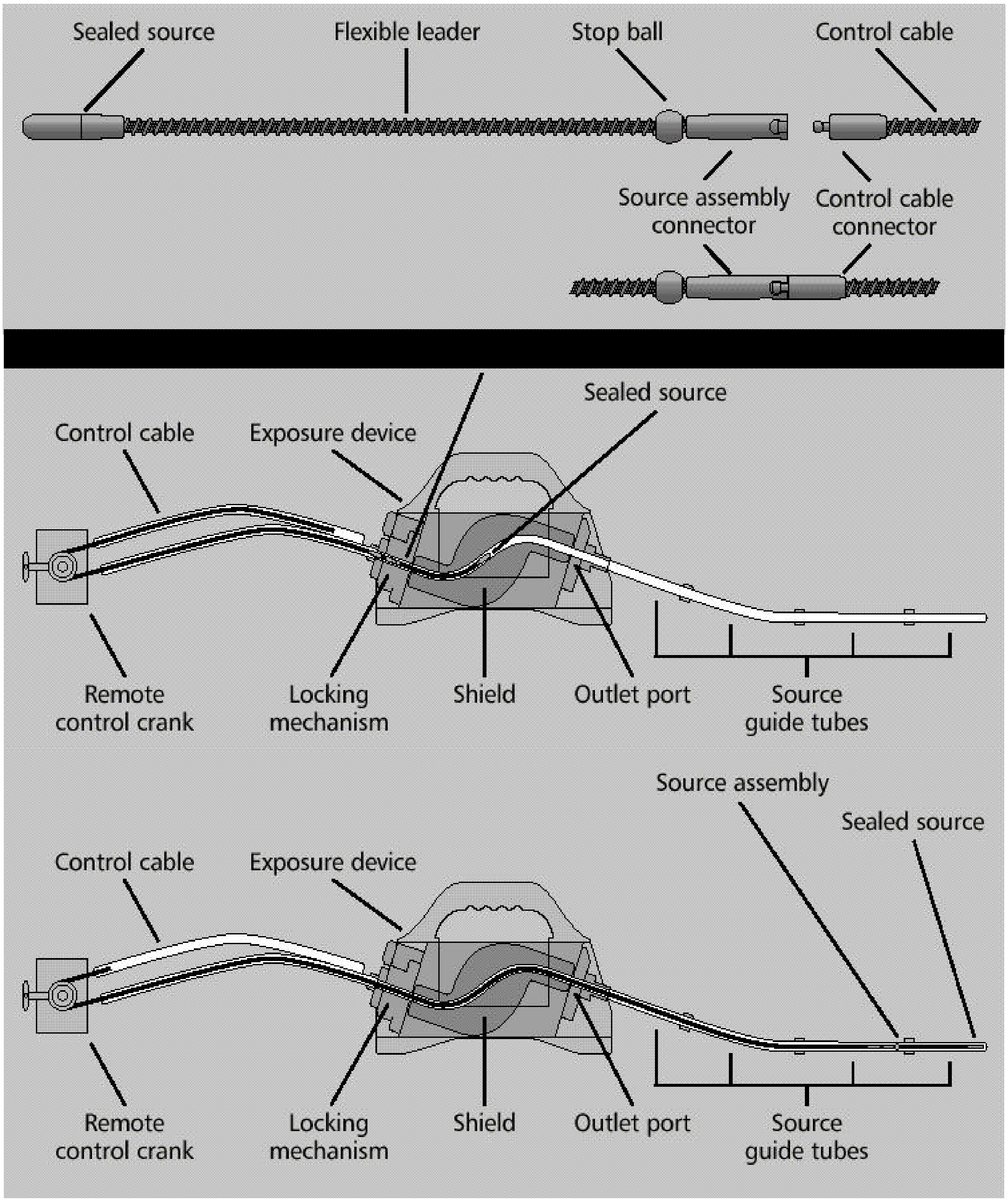
The internal construction includes several well-tried and tested design features selected from earlier models, but re-engineered into a novel configuration which has improved strength, operational performance, versatility, ease of use and safety. A schematic of the internal design can be seen in figure 2.

Figure 2 - Schematic of internal construction details



The source, pigtail and wind-out mechanisms were designed along familiar lines as can be seen figure 3.

Figure 2 - Schematic of the Source, Pigtail and Wind-out mechanism.



Development of the advanced second-generation ^{75}*Se*^{ntinel} Source

The development of the SENTINEL ^{75}Se source followed a similar path to the Model 880 series exposure device. The same development principles were applied. These involved close regulatory and industry involvement in the development process to define and feed back information on the design, the required performance and the safety requirements of the product. This was followed by rigorous safety and performance testing involving field trials by customers and prior regulatory authorisations necessary to use and validate prototypes.

Elemental ^{75}Se sources were first launched onto the market in the mid 1990's amid claims of enhanced image quality in the 3-30mm steel thickness range and with other benefits attributed amongst other things to the long 120 day half life. The source had a softer gamma ray spectrum and a lower specific gamma ray constant compared with ^{192}Ir and this meant it was easier to shield and operate in a reduced exclusion zone, which was perceived as providing a major safety and operational advantage.

Dateline: 1997

In early 1997 SENTINEL began to approach customers and industry leaders to establish the degree of commercial interest in this isotope and to determine if the development of a high quality SENTINEL brand would be justified. At that time it was not yet clear whether there would be a significant market for the nuclide and a key raw material, the highly enriched ^{74}Se needed for the activation targets was hugely expensive. The SENTINEL business team agreed a design brief, which would set the direction of the development program. It was decided to develop a highly compact ^{75}Se source, which would have the same dimensions as the SENTINEL ^{192}Ir source so it could be used in the widest variety of existing exposure devices already on the market. No specialist equipment would need to be purchased before the source could be used. It was clear from the outset that it would also be necessary to develop a low-cost supply route for the highly enriched ^{74}Se and lower-cost irradiation charges, both of which were too expensive for the market to bear at the time. This became a major focus for the project along with the design of the source itself.

The design team had to take into account the fact that selenium is highly volatile, chemically reactive and very toxic. The selenium melted at 270°C and it was necessary to be able to control the shape and size of the focal geometry to stop this moving around when the target melted during activation. The solution to this problem was the development of a unique quasi-spherical cavity in the capsule, which was octagonal in side view and circular in end view (see figure 3). This precisely defined the shape and size of the focal geometry. The target capsule was designed with two closure welds, one more than usual to provide added integrity. After activation, this was welded into an outer capsule and later welded one more time into a pigtail assembly, providing four closure welds in all.

Over the following year, the manufacturing procedures for processing the enriched target material into compact pellets and the assembly processes were perfected. The source capsules were subjected to a series of ISO, ANSI and Special Form tests to verify the product integrity and meet regulatory requirements before approval could be given to use and transport the product. The first generation design was marketed for a period of about 18 months after 1998 and used in early field trials, which confirmed previous reports and claims that real enhancements to image quality and contrast was achieved in the 3-30mm steel thickness range relative to ^{192}Ir.

Dateline: Spring 1999 - Development of the advanced second-generation ***$^{75}Se^{ntinel}$*** design.

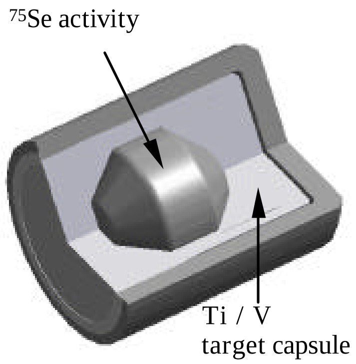
After gaining familiarity with the source and the use and handling of elemental selenium and after further consultation with customers and regulators it became apparent that the market for ^{75}Se sources might ultimately be limited by safety questions and concerns, which were being raised at the time about the suitability of using such a reactive and volatile material in source capsules. It is normal practice in radiation source design to use the most inert and stable materials possible. This is especially important for high activity sources and normally these are made with inert ceramics or noble metals as in the case of iridium, cobalt and ytterbium sources. In addition it was thought that market uptake of the product could also be limited by the continuing high costs of enriched ^{74}Se target materials and irradiation charges, so it was also necessary to deal with these issues.

It was therefore decided to initiate a new project in spring 1999 to see if it was possible to address all of these issues. The result was the fast-track development of the advanced second-generation ***$^{75}Se^{ntinel}$*** design which culminated in the launch of the advanced design in October 2000 at the 5th WCNDT in Rome. The development criteria, agreed with commercial, regulatory and safety managers was to produce an intrinsically safe product having high thermal stability as well as high physical integrity and to provide the industry and user community with a versatile source suitable for use with all types of exposure device with performance and safety designed-in.

Experiments were carried out to understand the nature of the interaction of elemental selenium with capsule materials as a function of temperature. It was found that selenium corroded both titanium and vanadium capsule materials above about 500°C and above the boiling point of 690°C the vapour pressure inside the capsule could rise significantly above atmospheric pressure. A study of the technical literature was undertaken to identify other potential candidate materials, which were more thermally stable, yet high enough in selenium content to produce a high activity source and which would not activate to produce unwanted radioactive impurities. This survey successfully identified a small, and not very well researched group of compounds known as metal-selenides, which at first sight appeared to meet all the criteria needed for thermal and physical stability.

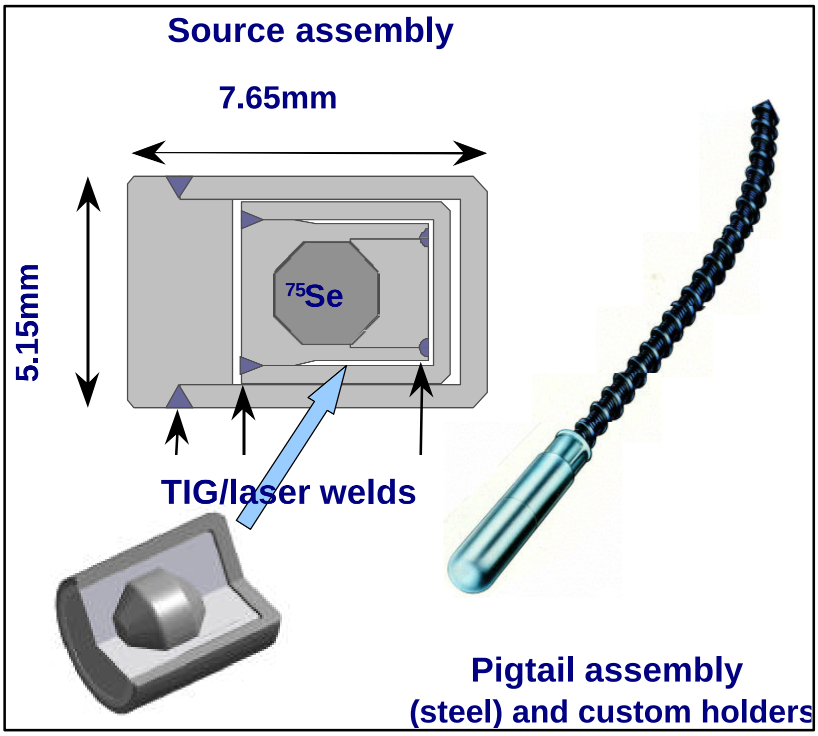
The project team proceeded to develop, test and optimise a working formulation and the production methods necessary to synthesis and press quasi-spherical shaped pellets to fit the capsule. This is now the subject of world patent WO 00/65608 (4). The main features of the advanced second-generation ***$^{75}Se^{ntinel}$*** source are shown in figures 3 and 4. There are four activity sizes shown in figure 3 with activities up to 3TBq. (80Ci) and the general assembly is shown in figure 4.

Figure 3 - *$^{75}Se^{ntinel}$* ™ Target Capsule Design



Pellet **(diameter)**	Focal Dimension **(diagonal)**	Activity **(Curie)**
2.00mm	**2.29mm**	**~15-20Ci**
2.50mm	**2.86mm**	**~30-40Ci**
2.85mm	**3.26mm**	**~45-55Ci**
3.25mm	**3.72mm**	**~70-80Ci**

Figure 4 - *$^{75}Se^{ntinel}$* Target, Source and Pigtail Assembly



Dateline: Spring 2000 - Field Trials
The first operational trials of the second-generation source were carried out in the North Sea by Solus Schall, a division of Oceaneering International in association with Stolt Offshore Ltd. These confirmed the performance benefits and operational safety advantages of the second-generation design.

The initial discussions while still at the theoretical stage, lead Solus Schall to believe that substantial benefits could be obtained in the 2”- 8” pipeline diameter range. With this in mind Solus Schall approached one of their major clients, Stolt Offshore Ltd and with their Pipelay Group it was agreed that major benefits to safety, quality, reliability and cycle times could be possible and they agreed to take an active part in trials.

Once the trial source release date was known, Stolt Offshore provided butt weld samples and released their in-house specialist to plan and finalise an extensive trial program and to support the safety case to allow the first operational application of $^{75}\mathbf{\mathit{Se}}^{ntinel}$ in the “North Sea” to commence. The basic scope of the trial covered safety, radiographic quality, flaw sensitivity, film processing, film and screen combinations and cycle times.

It was concluded that the safety features of the source, without question can reduce dose rates in the long term and reduce risks of the high levels of exposure previously experienced during incidents involving gamma ray sources [(1)].

The radiographic image quality has enabled the $^{75}\mathbf{\mathit{Se}}^{ntinel}$ source to be used where once only X-ray could be considered but without the inherent reliability problems associated with X-ray units, this is especially important for overseas and offshore locations where mobilisation of spares is a costly and problematic process. In line with the long working life of the source, cost benefits on change outs to overseas location are an additional benefit.

Dateline Summer 2000 - Integrity Tests

Thermal and physical integrity tests were carried out under a range of conditions and with a range of capsule types and material choices up to 1250^{o} C. Sources were tested and subsequently photographed and radiographed to observe the internal condition of the source capsules after the tests. Some of these data are provided below in the following figures. Figure 5 shows the results of Special Form integrity testing. These tests are required by regulatory authorities to demonstrate that sources are fit for purpose and suitable for transportation. Such tests need to be carried out according to strict procedures laid down by the regulations. Figure 5 (the central image) shows the results of the temperature test, which involves heating for 10 minutes at 800^{o}C. The right hand image is the result of the percussion test, which involves dropping a 25mm diameter 1.4kg mild steel bar from 1m onto a source capsule resting on a lead platform. It can be seen that the tests have negligible effect on the source and the integrity is well preserved.

Figure 5 - Special Form Integrity Test Results

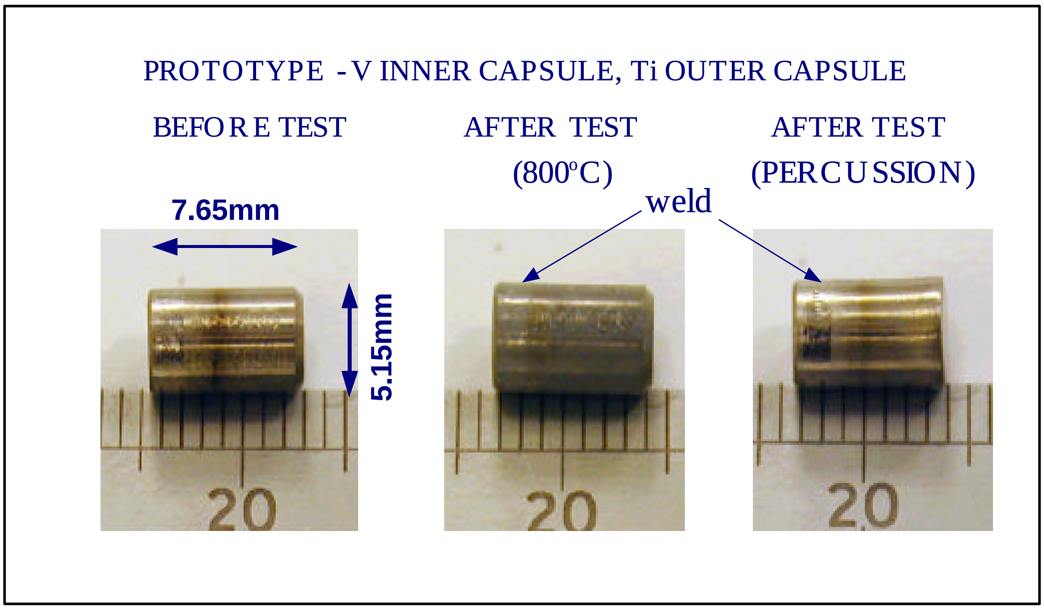
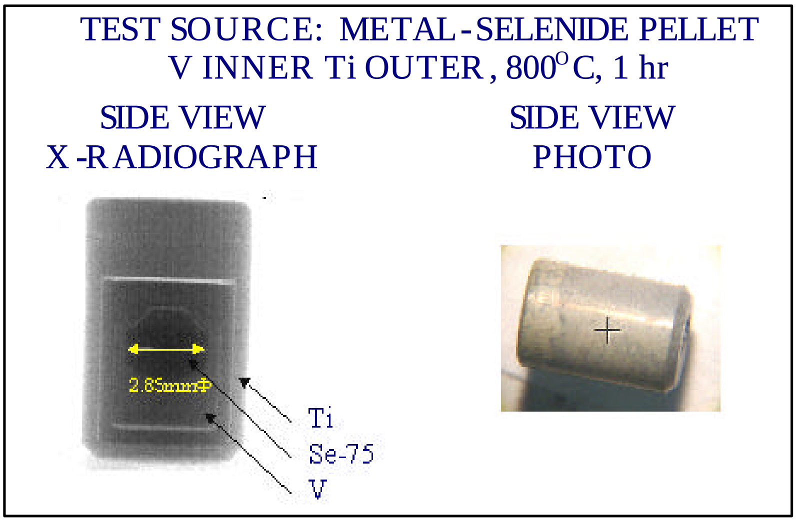


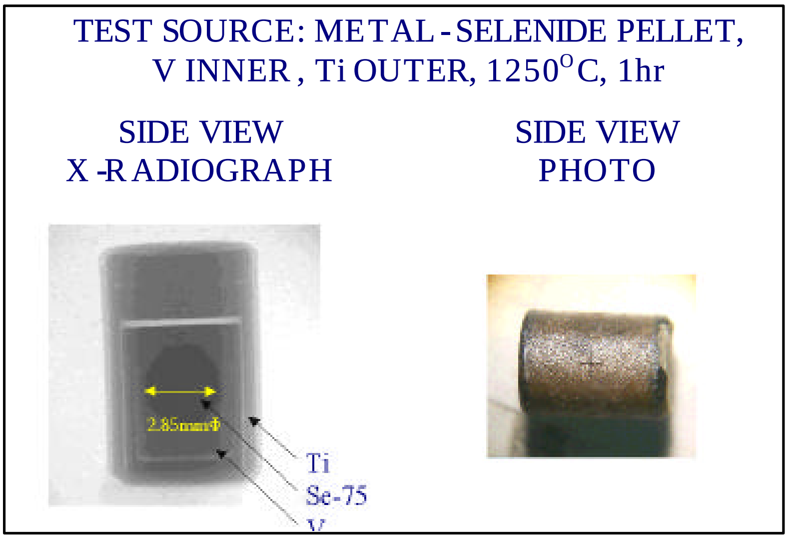
Figure 6 shows the results of heating a source to 800^{o}C for 1 hour. The X-radiograph on the left shows that the octagonal pellet, seen as a darker mass in the centre of the source is unaffected by the test and there is no evidence of any melting or interaction with the capsule wall. It can be seen that the external capsule has developed a thin surface oxidation coating, but the integrity of both the inner and the outer capsule is in tact.

Figure 6 - Thermal Test Results - 800°C



The two images in figure 7 show the results after a succession of trials, which involved heating the source for 1 hr at 800°C, then 1000°C, then for several hours between 1000 °C and 1200 °C and finally 1 hour at 1250 °C followed by gradual cooling over 24 hours. 1250 °C was the highest temperature achieved in the test program. It can be seen that the external titanium capsule became heavily oxidised and glazed over. However the internal capsule (vanadium in this test) appeared to be unaffected and its integrity remained in tact. The metal-selenide pellet retained its original shape and dimensions as did the whole inner capsule, indicating that any interactions between the materials of the capsule were minor. It was concluded that the metal-selenide pellet formulation had successfully achieved the design objective set out at the beginning of the project.

Figure 7 - Thermal Test Results - several temperatures up to 1250°C



Dateline Summer 2001 - Continual Improvement

Projects such as this are often open-ended. The needs for continual improvement means that design, processes and safety are all under continual review. At the time of writing special capsule materials are continuing to be investigated, which are able to withstand prolonged heating without significant oxidation at a temperature of 1300°C. These are options for the future, which could replace the titanium or grades of steels normally used for source outer capsules, both of which oxidise and eventually burn away after prolonged heating at very high temperatures in air. Their potential use in the future would depend on regulatory and industry driving forces.

The need for high thermal integrity and safety for all types of gamma radiography sources has been discussed by Ballaux[2] In his paper it is proposed that gamma radiography sources should be capable of withstanding the intense heat of a petroleum fire at 1200°C for 1 hour without the release of significant dispersible radioactivity.

Conclusions and Summary

Safety and performance can be designed into gamma radiography products, by a process, which involves whole-industry collaboration. In this way, products are in effect, developed by the Industry for the Industry to meet Industry needs. The involvement of users, industry leaders, regulators, safety officials and designers is necessary to ensure that right products are developed with right safety and performance features necessary to fully meet both current-day and future Industry standards and regulations throughout the world.

Acknowledgements

We would like to thank the very many contributors who helped to develop the Model 880 exposure device and the ***^{75}Se^{ntinel}*** source and also to all other contributors who supported this work in indirect ways.

Field Trialists:
Electrothermal, Scotland; Mat Eval NDT, Singapore; IRIS NDT, Canada; Arliss Welding, England; Canspec, Canada; Cooperheat-MQS, USA; Global X-Ray, USA; Chinook Testing, Canada; Longview Inspection, USA; Conam Inspection, USA; Capital X-Ray, USA; Huntington Testing & Technology, US; Solus Shall, a division of Oceaneering, UK; Stolt Engineering UK; AGFA Geveart Ltd.

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