depths [8]. This implies that the trapping levels are not associated with the activators, but that they are the defects in the host lattice. This investigation suggests that these defects are likely to be sulphur (S^{2-}) vacancies.

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Coefficient of thermal expansion of sulphamate nickel electrodeposits

At Sandia Laboratories, Livermore, electroplating is used to join metals that are difficult to join by conventional techniques [1-3]. A taper is cut on the metals to be joined, then they are mated and held together while electroplating is used to fill the triangular segment created by the tapers. Of the deposits used to provide the "filler material" of the joint, nickel has found the most usage.

Ideally, the thermal coefficient of expansion of a deposit used for a joining application should match that of the other materials comprising the joint. This is particularly true for applications at elevated temperatures where distortion could occur due to differential expansion of components of the joint. Very little published information is available on this property for nickel electrodeposits. Brenner *et al.* [4] published data for nickel deposits produced in a Watts solution and Safranek and Schaer [5] for deposits produced in a sulphamate solution. Since an application existed wherein a plated joint was to be part of a structural configuration subjected to temperature variations between room temperature and 300° C, thermal coefficient of expansion data were obtained in our laboratory for sulphamate nickel deposits.

Two sulphamate plating solutions were used. They were of the same composition but differed in volume and age. Chemical formulation and operating conditions are presented in Table I. Nickel tubes were electroformed by plating on aluminium and then dissolving the aluminium in hot caustic solution. The tubes had an outside diameter of 9.5 mm (0.376 in.), a wall thickness of 0.5 mm (0.020 in.), and a length of 51 mm (2 in.).

After electroforming, a tube was placed in the bottom of a 0.91 m (3 ft) long closed-end quartz tube. A quartz rod, connected to the core of a Linear Variable Differential Transducer (LVDT) was placed on top of the nickel tube. The top end of the quartz tube was attached to the case of the LVDT. A chromel–alumel thermocouple was

TABLE I Composition and operating conditions for nickel sulphamate solutions

Code	A* and B†
Nickel	81 g l^{-1}
Nickel sulphamate	450 g l^{-1}
Boric acid	40 g l^{-1}
Surface tension	38 dyn cm^{-1}
pH	3.8–4.0
Anodes	Sulphur depolarized
Current density	268 A m^{-2}

*Solution volume was 40 litres. Electrolysis time was 6 Ahl^{-1}.

†Solution volume was 120 litres. Electrolysis time was greater than 250 Ah l^{-1}.

TABLE II Thermal expansion data for nickel sulphamate deposits

Temperature range (°C)	Expansion coefficient, 10^{-6} °C^{-1}			
	Solution A*†	Solution B*†	Safranek and Schaer‡	Metallurgically treated nickel§
25–50	10.2	8.5		
25–75	12.6	12.0		
25–98	13.2	13.2		13.3
25–122	13.6	13.2		
25–147	13.5	13.5		
25–172	13.6	13.6		
25–195	13.7	13.7	13.6	13.9
25–222	13.8	13.8		
25–247	14.2	14.0		
25–271	14.3	14.2		
25–295	14.4	14.3	14.2	14.4
25–319	14.6	14.5		
25–342	14.9	14.5		
25–367	15.1	14.7	14.8	

*See Table I for solution composition and operating conditions.

†Average for four specimens.

‡See [5].

§Electrolytic nickel fused in vacuum, annealed, cold swaged and annealed. See [6].

attached to the nickel sample and the assembly placed into an oven with the top of the quartz tube and LVDT outside the oven. The LVDT and thermocouple were connected such that a continuous plot of expansion versus temperature was obtained. This plot included expansion from the quartz. By subtracting this expansion from the quartz for the length of the nickel tube and dividing by the sample gauge length, a plot of percentage expansion of the nickel tube versus temperature was obtained. The thermal coefficient of expansion was calculated for a number of separate points using the secant coefficient from the desired point back to room temperature.

The data are summarized in Table II. The scatter for temperatures up to 100° C is attributed to the heating rate of the furnace and the temperature gradients that still existed in the specimen. The accuracy of the test above 100° C was about 5% and the individual data from each set of deposits fell within this range. Deposits from solutions A and B were quite similar in thermal expansivity even though solution B had seen much more usage. Data of Safranek and Schaer and for metallurgically treated nickel, also included in Table II, show very good agreement with the data for solutions A and B.

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