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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-10200

BUTTONHEAD ANCHORAGE OF TENDON WIRE
FOR THE FORT ST. VRAIN PRESTRESSED CONCRETE REACTOR VESSEL

by

J. F. Hildebrand

Prepared under
Contract AT(04-3)-633
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

June 22, 1970

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SUMMARY

The High-Temperature Gas-Cooled Reactor which Gulf General Atomic Incorporated designed and is constructing at Fort St. Vrain uses a prestressed concrete reactor vessel (PCRVR) to contain the reactor core, the helium primary coolant, the helium circulators, and the steam generators.

The prestressing forces are provided by a system of 448 posttensioned, nongrouted tendons. These tendons, which consist of 169 high-strength 0.250-in.-diameter wires, depend on the positive anchorage of the cold-upset buttonheads as well as the tensile and stress-relaxation properties of the wire. The investigation of the ability of the buttonhead to support the ultimate tensile strength of the wire is the subject of this report.

These investigations included (1) a review of the wire manufacturing process, (2) the characteristics and properties of the finished wire, (3) the types and methods of forming buttonheads, (4) the effect of malformations and imperfections on the strength of the buttonheads, and (5) metallographic examinations of the various conditions that occurred during the test programs and during fabrication and installation of the tendons.

The WCS 1.5FS Head-Seat System* was selected and first tested using domestic stress-relieved wire and then using low-relaxation Thermalized** wire. Well over 3000 tensile tests, most of which used specimens with buttonheads at each end, have demonstrated that the buttonhead not only supported the ultimate tensile strength of the wire, but it was not degraded by minor imperfections produced by the upsetting operation. Less than 0.5% of the buttonheads failed.

*Trademark of Western Concrete Structures, Gardena, California.

**Trademark of Richard Johnson and Nephew, Ltd., Manchester, England.

The strength of the buttonhead was not diminished by fatigue loads; in fact, cycling in tension between 138 and 170 ksi (mean load equivalent to 60% of wire ultimate strength), buttonheads survived 40-million cycles.

The results of the test program, which covered a 3-yr period, confirm that the buttonheads provide the positive wire anchorage needed for the tendons of the Fort St. Vrain PCRV.

INTRODUCTION

In September 1966, Gulf General Atomic Incorporated (GGA) commissioned Western Concrete Structures (WCS) to perform systems engineering, conduct a test program, and furnish a prestressing system for the Fort St. Vrain prestressed concrete reactor vessel (PCRV). The design prerequisites stated that the system must develop the prescribed forces using a positive end-anchorage system and that it must be ungrouted to facilitate inspection, restressing, and replacement in the event such action might become necessary during the 30-yr design life of the PCRV. The posttension system selected consisted of tendons having many single wires connected to the anchor assembly by cold-upset (buttonheaded) ends. The general anchor assembly arrangement is shown in Fig. 1.

The 0.250-in.-diameter tendon wire was required to comply with ASTM Specification A421-65, type BA. As such it had to be cold-drawn, stress-relieved (SR), and suitable for cold-upsetting to produce an end-anchor deformation or buttonhead.

An important feature of any wire for a PCRV tendon is its long-term stress-relaxation property. If the initial stress on tendons decreases significantly, additional tendons or a costly restressing of the PCRV may be required. To preclude these possibilities, GGA specified that the wire have a relaxation loss not to exceed 8% over a 30-yr period. Since a GGA test program (Ref. 1) indicated that domestic SR wire had an indicated 30-yr loss greater than 8%, and in addition was somewhat unpredictable, the claims by British wire manufacturers that they had produced low-relaxation (LR) wire with predictable constancy were investigated.

It was found that Richard Johnson and Nephew, Ltd. (RJ&N), as a licensee of the Somerset Wire Co., Ltd.,* produced LR Thermalized wire,** which not only met ASTM specifications, but its long-term relaxation loss was indicated to

*British patents 748357, 969191, and 969129.

**SR wire refers to domestic stress-relieved wire, and LR wire refers to RJ&N's Thermalized low-relaxation wire.

Fig. 1. Tendon end anchor assembly arrangement

be less than half that of the GGA requirement. Thus, it was uniquely suitable for use in the Fort St. Vrain PCRV. Before making a final decision to use the wire, however, a full-size tendon-test program was undertaken to further evaluate the stress-relaxation properties (Ref. 1). In addition, sample coils of the wire were obtained to evaluate its cold upsetability and to determine the tensile and fatigue properties of individual wire-test specimens having cold-upset ends for gripping purposes.

Different kinds of cold-upset deformations have been used as wire anchors for years, probably dating back to the advent of the nail. Indeed some of the early prestressing wire was anchored using a simulated nail-head cold-upset. Modern wire upsetting, however, deforms the wire less drastically and produces a more efficient anchor than a nail-head upset. One common design is the tulip-shape developed by Bureau BBR, a European organization widely recognized in the field of prestressed concrete structures. Western Concrete Structures, as their licensee, started using tulip-shaped anchors in 1953, but about 1964, through a program seeking to improve anchor design and reliability, developed their own 1.5FS Head-Seat System. When this system was proposed for the PCRV tendons, it had already been accepted for commercial structures. Nevertheless, GGA conducted the tests and investigations as discussed herein to ensure that the WCS buttonhead was indeed acceptable for use in the Fort St. Vrain PCRV.

While it would seem pertinent to include the results of corrosion and irradiation tests, this information has already been reported in considerable detail (Ref. 2). It suffices to say that the corrosion-inhibiting coatings prescribed for the wires and tendons provide an excellent corrosion protection system.

WIRE MANUFACTURING

Before considering the tests relating to the cold-upset buttonheads, it is necessary to examine the process used and the mechanical properties produced in making the wire. Virtually all prestressing wire, whether U.S., British, or Japanese, meets the requirements of ASTM A421. The steel usually contains between 0.72 and 0.93% carbon, 0.4 to 1.10% manganese, 0.10 to 0.35% silicon, and 0.04% (max) phosphorous and sulfur. Cast ingots are rolled to make billets that are subsequently hot-rolled to produce rods of a diameter suitable for drawing into the finished wire gage. As the first of many inspections, RJ&N prepares a sulfur print from both ends of each rod coil to determine the size and distribution of the sulfide inclusions, which are indicative of segregation. Rod coils are also hot-acid etched to detect significant rolling defects. From past experience they have developed an internal standard on which they base their rejection or acceptance of rods for further processing to make prestressing wire.

Rods are always patented before being cold-drawn to produce the uniform and fine pearlitic microstructure needed for good drawability. [Patenting is a form of heat treatment for which the time and temperature are governed largely by the composition of the steel rod (Ref. 3).] The rod is usually austenitized (heated at 900° to 1000°C from 1 to 5 min) in a furnace having a neutral atmosphere and is then quenched in a bath of circulating molten lead at 450° to 550°C. Several lines of rod move continuously through the furnace and bath. At RJ&N the rod was austenitized at 980° to 1000°C and quenched at 530° to 550°C with the rod moving at about 5 ft/min.

Following patenting, the rod is cleaned by pickling, phosphated, and borax coated to facilitate the pickup of soap lubricant during the cold-drawing operation that is done continuously on a 4- or 5-die draw-bench. To make the drawing operation continuous, the rod ends are joined by an electrical resistance butt-weld which is marked using a copper sulfate solution and is later cut out of the finished wire.

From this point in the process the drawn wire is treated differently to make SR and LR finished wire. To make SR finished wire, the drawn wire is first roller-straightened and then stress relieved by being passed through a bath of molten lead maintained between 400° and 450°C. To make the LR finished wire, the drawn wire is simultaneously stretched and heated using the patented process conceived by the Somerset Wire Co. (Ref. 4). As their licensee, RJ&N modified the basic process to produce Thermalized wire.

In essence the Thermalizing process consists of using two capstan wheels of slightly different diameters which strain the wire about 3% as it passes continuously through a bath of molten lead maintained between 400° and 425°C (Fig. 1a). The process also straightens the wire, which, in fact, must not be roller-straightened lest the LR properties be destroyed. At RJ&N (Ref. 5) they have found that a thermal gradient occurs in the wire as it passes through the lead bath. As a result the wire experiences a gradient of strains, some of which are above the elevated temperature elastic limit; the hotter surface experiences more plastic deformation than the slightly cooler center. On cooling under load following the lead bath treatment, the thermal stresses created in the skin tend to compress the core radially, producing a compensating longitudinal tensile stress. In addition, upon un-stressing the wire, the core, in attempting to revert to zero elastic strain, imposes a longitudinal compressive stress in the skin layers. It is believed that the nonuniform stress distribution produced in the wire is partly responsible for the desirable LR property of the Thermalized wire, and may be a contributory cause of the buttonhead slip malformation, as will be discussed later.

Fig. 1a. Continuous wire Thermalizing process (courtesy of RJ&N)

WIRE PROPERTIES

As a candidate material for the PCRV tendons, 11 coils of Thermalized wire were purchased by GGA late in 1967 for tests and evaluation. Most of this wire was used to prepare full-size tendons for stress relaxation, fatigue, and tensile tests (Ref. 1), and for bend and buttonhead tensile tests of the wire (Ref. 6). The tensile properties of these coils as reported by RJ&N, and as determined by GGA (Table 1), exceeded the requirements of ASTM A421; no significance is attached to the fact that the GGA values of ultimate strength were slightly higher than those of RJ&N, and the elongations were slightly lower.

Metallographic sections were prepared from three samples of each coil; the microstructure, an optically unresolved pearlite, was similar and quite uniform in all the samples although a slight degradation was evident in the surface layer of some samples. (See Fig. 2.) Microhardness measurements confirmed that a surface layer was somewhat softer than the sublayers, possibly because of a partial decarburization that occurred during or prior to the patenting process. The average hardness of the wire was generally Rockwell C 46; the microhardness measurements actually indicated a range from 44 to 48 R_c , but it must be remembered that the averaging ability of a 200-g indentation is small when compared to the 150-kg indentation of the standard Rockwell C measurement.

TABLE 1
TENSILE PROPERTIES OF THERMALIZED WIRE TEST COILS

Coil No.	Source of Data	TS (ksi)	YS (ksi)	Elong. (% in 10 in.)	RA (%)
50/365	RJ&N	254.6	231.4	6.4	
50/365	RJ&N	240.3	--	5.6	
50/365	GGA	255.4	224.0	-	39.1
50/365	GGA	255.4	224.0	5.8	40.5
50/365	GGA	255.4	226.1	5.7	40.5
50/366	RJ&N	252.6	230.1	6.8	
50/366	RJ&N	250.1	--	6.2	
50/366	GGA	253.8	224.0	5.8	39.1
50/366	GGA	255.4	217.9	5.8	42.2
50/366	GGA	253.4	220.0	5.5	39.1
50/367	RJ&N	251.4	228.5	5.9	
50/367	RJ&N	250.1	--	5.6	
50/368	RJ&N	248.5	227.3	6.8	
50/368	RJ&N	248.9	--	6.5	
50/368	GGA	252.1	220.0	8.2	42.2
50/368	GGA	252.1	224.0	8.0	42.2
50/368	GGA	253.4	224.0	6.3	43.0
50/369	RJ&N	248.9	226.9	6.3	
50/369	RJ&N	248.5	--	5.6	
50/369	GGA	252.9	224.0	5.5	43.4
50/369	GGA	250.9	223.0	5.8	43.0
50/369	GGA	248.9	218.2	5.0	43.4
50/370	RJ&N	251.8	230.6	6.2	
50/370	RJ&N	247.3	--	5.6	
50/371	RJ&N	250.5	226.1	6.0	
50/371	RJ&N	249.3	--	6.2	
50/371	GGA	253.8	224.0	6.3	40.5
50/371	GGA	253.8	220.0	6.2	39.1
50/371	GGA	252.5	222.0	6.2	39.1
50/372	RJ&N	251.8	228.1	6.8	
50/372	RJ&N	252.2	--	6.5	
50/372	GGA	254.6	222.0	6.0	40.9
50/372	GGA	252.1	226.1	6.0	40.5
50/372	GGA	254.2	222.0	6.3	40.9
50/373	RJ&N	250.9	228.1	6.5	
50/373	RJ&N	249.3	--	6.8	
50/373	GGA	251.7	222.2	5.9	42.6
50/373	GGA	250.1	220.2	6.2	43.4
50/373	GGA	250.5	219.2	5.8	44.4
50/374	RJ&N	250.5	227.3	7.1	
50/374	RJ&N	250.9	--	6.9	
50/374	GGA	255.8	224.0	6.6	40.5
50/374	GGA	252.5	222.0	6.0	38.5
50/374	GGA	251.3	220.2	6.5	41.0
50/375	RJ&N	248.9	224.1	6.2	
50/375	RJ&N	246.1	--	5.6

M25784-2

(200x)

M25784-1

(200x)

<u>Location</u>	<u>DPH</u>	<u>R_c</u>
1	401	40.8
2	447	45.3
3	473	46.9
4	490	48.4

Fig. 2. Surface microstructure and microhardness. Surface layer was softer than sublayers

COLD-UPSETTING MACHINES

Besides the wire manufacturing process variables, another important factor to be considered in the formation of buttonheads is the cold-upsetting machine. Until recently the common practice was to use mechanically operated machines for both shop and field heading, although some hydraulically operated machines were also available for field heading. The WCS practice for both shop and field heading is to use a hydraulically actuated machine which they developed. The WCS machine has a die-block that is normally attached to the control console for bench use, but it may be remotely connected for field use. By suspending it near the end of the tendon, it may be swung onto the wire, whereas if it were floor-mounted the wire would have to be whipped into the die-block.

All of the machines function similarly in that wire is firmly gripped and then upset to form the head; the differences lie in the method of gripping and upsetting. The mechanical machines grip the wire through a linkage system and the upsetting die is actuated by a cam; hence, the upsetting rate is not easily adjusted and the adjustment for head eccentricity control is limited. The WCS hydraulic machine can be adjusted to correct for eccentricity and the upsetting time and the applied force can be regulated through the hydraulic system of the machine.

The WCS die-block essentially consists of two perpendicularly positioned hydraulic cylinders that operate in a horizontal plane; one moves the gripping die, the other moves the upsetting die. (See Fig. 3.) The stationary side of the split gripping die has adjusting screws that align the wire groove with the center of the upsetting die cavity. The moving side has a floating head that self-aligns on the wire as the die closes. A unique feature of the wire groove is the divided bearing surface shown in Fig. 4. When the die closes, the wire hole is intended to be slightly smaller than the wire diameter to prevent slippage during the upset. To compensate for diametral

135-127-6

Fig. 3. Die-block of the WCS buttonheading machine

Fig. 4. Wire gripping die

variations of the wire, the central cavity allows the wire to swell elastically such that it tends to jamb against the edge of the grip cavity. Note that the gripping dies close on the wire with a clamping force of 65 kip. It is applied for approximately 5 sec during which time the upsetting force (30 kip) operates from 2 to 3 sec.

The WCS machine uses a shaped-cavity upsetting die. It has conical sides and hemispherical bottom with a diameter slightly larger than the wire, a design which allows the upset metal to form freely while at the same time maintaining concentricity. The flat seat and wire-to-seat fillet of the buttonheads are formed by the shape of the gripping die as shown by the sequence in Fig. 5.

The WCS buttonheading machine has several mechanical adjustments of the dies as well as pressure settings and timer controls. As previously mentioned, the fixed half of the clamping die has an adjustment to permit aligning the clamped wire with the center of the upsetting die cavity. The hydraulic ram of the upsetting die has two adjustments; one determines the amount of wire indexed for upsetting (I in Fig. 5), and the second limits the upsetting travel. The adjustments are interdependent, which tends to make the proper adjustment a somewhat tedious operation, but once the machine is properly set, it operates smoothly and requires very little maintenance. The buttonhead produced has the shape and microstructure shown in Fig. 6. Note also the excellent grain-flow pattern in the head-to-wire fillets.

WIRE POSITIONED
FOR UPSETTING

PRIMARY UPSETTING
DEFORMATION

SECONDARY UPSETTING
DEFORMATION

COMPLETED BUTTONHEAD

Fig. 5. Buttonhead fabrication sequence (F_1 = gripping force, F_2 = upsetting force)

Cold formed by upsetting wire

Cold worked microstructure

K-75-464

Grain flow pattern in head-wire fillet

Fig. 6. Buttonhead shape plus microstructure

HEAD-SEAT SYSTEMS

Three head-seat systems deserved consideration in the development of the system used on the RJ&N wire of the tendons for the Fort St. Vrain PCRV. In fact, WCS investigated several variations of these systems; the tests and results are reported in detail in WCS Technical Report No. 6 (Ref. 6).

During the 1950s and early 1960s, the tulip-shaped buttonhead was considered to be the standard for wire prestressing systems. Its ball shape had no bearing surface (see Fig. 7) and it depended on a relatively soft steel plate into which it could embed and seat itself. WCS presented evidence to show that when the tulip-shaped buttonhead seats, the upset metal around the wire hole in the plate pinched the wire just under the buttonhead, and the triaxial stress field created in the wire led to premature failure. As shown in the sketch below, the upset seat essentially strangles the wire.

TULIP-SHAPED HEAD

Fig. 7. Tulip-shaped buttonhead

The next stage was the development of a large radius fillet between the buttonhead and wire, but still there was essentially no bearing surface. The seat again was soft steel, and the wire holes were unchamfered. This system performed only slightly better than the tulip-shaped buttonhead.

TULIP-SHAPED HEAD
WITH LARGE FILLET

The investigations continued with tests to determine the most favorable seat characteristics as well as the configuration of the buttonhead. The WCS 1.5FS Head-Seat System* that evolved from these tests had a buttonhead with a small fillet (0.015 to 0.040 in.) and a flat bearing surface. The edge of the seat hole was slightly chamfered to relieve the buttonhead fillet, and the optimum hardness range of the seat was found to be R_c 36 to 44; it was later specified as R_c 38 $\pm$ 2. This arrangement effectively prevented seat deformation and eliminated failures associated with the strangulation stresses.

WCS BUTTONHEAD

All of the developmental, qualification, and production tests discussed hereafter used a seat complying with the features described and used hole dimensions as shown in Fig. 8. The Fort St. Vrain tendon anchor hardware prepared from AISI 4142 steel was likewise required to have a hardness of R_c 38 $\pm$ 2 and to have wire holes conforming to the stated dimensions.

*Covered by U.S. Letters Patent No. 3,437,359.

BUTTONHEAD FAILURE DEFINED

Because of the strangulation effect observed during their use of the tulip-shaped buttonhead, WCS arbitrarily defined a head failure to have occurred when a tendon wire loaded in tension fractured through the head or in the wire within one wire diameter of the head bearing surface. This definition has prevailed, although their developmental tests showed that hard seats (R_c 35 to 45) supporting the WCS buttonheads did not subject the wire to strangulation, hence fractures rarely occurred in or near the head.

At the time the WCS report (Ref. 6) was prepared, over 12,000 production buttonheads on SR wire had been tested on full-size tendons as well as individual wires; none of the buttonheads failed in the defined manner.

BUTTONHEADS ON STRESS-RELIEVED WIRE

As a corollary to the definition of a failure, it was important for GGA to establish limits for buttonhead malformations and imperfections. To this end, 153 buttonheads on the first test tendon having SR wire were examined following a load-cell calibration test in which the tendon was stressed to 75% of its guaranteed ultimate tensile strength (GUTS). The buttonheads and seats conformed to the WCS 1.5FS Mk 1 dimensions as shown in Fig. 8. None of the heads failed, although visual examination revealed the following conditions.

Sound heads, no imperfections		59
Splits, single	67	
double	2	
Slips, single	18	
double	7	
Total imperfect heads		<u>94</u>
		153

A split was defined as an open crack where the two crack surfaces were not in contact and the crack was oriented parallel to the axis of the wire. A slip was defined as a shear crack where the two crack surfaces remained in contact and the crack was oriented at approximately 45° to the axis of the wire. Some examples of these imperfections are shown in Figs. 9 and 10. None of the splits extended into the bearing surface of the buttonhead. But, to determine the cause and extent of the damage, four of these buttonheads were prepared for metallography by cutting the wire close to the head and polishing to the bearing surface. On that surface, the open split was not visible, but the closed slips were seen as radial cracks. Further polishing revealed the split and it was found to be associated with inclusions in the wire. (See Fig. 11.) The slips were found to be associated with a severely cold-worked microstructure. (See Fig. 12.)

1. HEAD ECCENTRICITY: 0.030-IN.
MAX TOTAL INDICATED READING
2. SEAT ECCENTRICITY: 0.015-IN.
MAX TOTAL INDICATED READING

Fig. 8. WCS 1.5FS Mk 1 Head-Seat System

M20397-1

(3x)

Fig. 9. Split imperfections. Buttonhead at right shows a combination split and slip. (Scale is 0.01 in./div.)

M20398-1

(3x)

Fig. 10. Slip imperfections. Buttonhead at right is perfect. (Scale is 0.01 in./div.)

M20395-1-1

(8x)

(Scale is 0.01 in./div.)

M20397-1-1

(100x)

Fig. 11. Microstructure of a split. On a plane $\frac{3}{32}$ in. from bearing surface, the split was revealed to be associated with inclusion in wire

M20398-1-2

(Scale is 0.01 in./div.)

M20398-1-4

(100x)

Fig. 12. Microstructure of a slip. On a plane $\frac{3}{32}$ in. from bearing surface, the slip was revealed to be associated with a severely cold-worked microstructure

The next opportunity to examine buttonheads occurred when SR wire was used for another full-scale test tendon (Ref. 1). In this case the buttonheads on one end were shop fabricated at WCS; the other end was field buttonheaded at the GGA test site. A visual examination of all the heads revealed the following ratios of heads with slip and split imperfections.

<u>Condition of Heads</u>	<u>Field End (%)</u>	<u>Shop End (%)</u>
Sound	81	90
Splits	9	9
Slips	10	1

None of the buttonheads failed when the tendon was loaded in tension to failure -- tendon failure being defined as the failure of 5 or more wires.

Concurrent with these early tendon tests, samples of buttonheaded SR wire were sent to the Applied Research Laboratory of U.S. Steel for fatigue tests (Ref. 7). The test parameters and results are discussed later.

BUTTONHEADS ON THERMALIZED WIRE

When the advantages of using LR Thermalized wire in the PCRV prestressing system became apparent, enough wire to make a test tendon was ordered from RJ&N. The tendon and related tensile-test specimens provided the first opportunity to examine 1.5FS Mk 1 buttonheads on LR wire.

The number of heads with split and slip imperfections is shown below as a comparison between the shop- and field-fabricated heads.

Buttonhead Condition	Shop Fabricated	Field Fabricated
Sound	0	2
Slips	90	62
Splits	2	22
Slips and Splits	<u>76</u>	<u>78</u>
Total	168	164

It was obvious that the Thermalized wire was more susceptible to imperfections than the SR wire. None of the slips or splits entered the wire proper, however; rather, they appeared to stop at the edge of the bearing surface. Splits could not be related to any visible surface condition of the wire.

The tendon fabricated from the wire was subjected to an ultimate tensile load test until about 14 wires failed, but none could be classified as a buttonhead failure.

A cursory test was then conducted to compare the buttonheads on SR wire with those on Thermalized wire using the same buttonheading machine. The results revealed again that the Thermalized wire was susceptible to slip imperfections.

Buttonhead Condition	SR Wire	LR Wire
Sound	3	2
Splits	19	3
Slips	0	11
Splits and Slips	<u>0</u>	<u>4</u>
Total	22	20

Typical buttonheads from the test tendon are shown in Fig. 13. Other heads, prepared for metallographic examination on the plane of the bearing surface, revealed, as was observed on the SR wire heads, that the splits were associated with inclusions, and slips were associated with excessive cold work. Some other features of the cold-upset wire are shown in Fig. 14.

Concurrent with the preparation of the LR tendon, test samples of Thermalized wire were Metabond (International Rustproof Company's brand of zinc phosphate) coated for corrosion protection and buttonheaded prior to being returned to RJ&N for a fatigue test. The features and ramifications of the test are discussed in another section.

M23200-1

(4x)

M23200-2

(4x)

Fig. 13. Buttonheads on Thermalized wire; top: head Nos. 4 and 6 exhibit small splits; head Nos. 1, 2, 3, and 5 exhibit slips; bottom: all heads exhibit various forms of slips

M19504-4

(6x)

M19504-2

(6x)

M19504-1

(6x)

Fig. 14. Features of early buttonheading; top: flash on the bearing surface resulting from a gap between the gripping dies; bottom: brinelling of the wire resulting from wire slippage in the gripping die.

FAILURE OF BUTTONHEADS ON THERMALIZED WIRE

A second trial shipment of wire consisting of 11 coils was received from RJ&N for the fabrication of a circumferential test tendon. When it was finished, WCS investigators observed that all 340 buttonheads exhibited relatively severe cracking. They then prepared 373 tensile test specimens representing 3 coils of wire, all from one heat of steel, and for comparison they also made 150 specimens using some stress-relieved wire produced by Shinko Wire, Japan. When tested, none of the WCS 1.5FS Mk 1 buttonheads on the Shinko wire failed; 10 failed on the RJ&N wire. Of these 10 failures, 6 were at loads below the minimum tensile strength of the wire. The WCS investigators (Ref. 6) described the failure as being tubular; that is, the wire appeared to have pulled out of the buttonhead, leaving a cylindrical cavity. Typical examples of these failures are shown in Figs. 15 and 16.

It was evident from the fracture texture that the origin was in the head and seemed to be related to the rather large split present in each case. Several of the buttonheads were sectioned for metallographic examination, primarily seeking evidence of metallurgical deficiency. The only evidence uncovered was a severely worked structure associated with a branch crack in the head (Fig. 17) and with the tubular, shear fracture (Fig. 18).

Metallographic sections of several other buttonheads on Thermalized wire were also prepared for microhardness measurements. It was important at this point to determine the effects of upsetting on the microstructure and hardness (tensile strength) of the wire. Figure 19 shows the structure and the location of some typical hardness indentations. Figure 20 shows the location and hardnesses of other samples. As expected, the hardness of the upset metal was slightly higher than the wire but not sufficiently so to account for premature failure of Thermalized wire buttonheads.

M24707-1

(4x) M24708-1

(4x)

50/367/67 ← COIL → 50/370/67

Fig. 15. Typical tubular failures. Fractures of buttonheads from Thermalized wire tests. Flattened flash (F) and origin of fracture (O) are indicated. Fractures on wire were damaged by recoil against anchor hardware. Note eccentricity of bearing surface on left buttonhead

M24707-3

(4x) M24708-3

(4x)

50/367/67 ← COIL → 50/370/67

Fig. 16. Typical tubular failures. Buttonhead failures consisted of a tensile-type fracture (T) and a shear-type fracture (S). Point (X) is shear face of a buttonhead slip. Points (O) and (F) are origins of fracture and flash, respectively

M25772-2

(8x)

M25772-1

(100x)

Fig. 17. Microstructure of tubular failure. Arrow in top view indicates area shown in bottom photo where the arrow indicates a cold-worked structure

M24712-1,-2

(100x)

Fig. 18. Tubular, shear fracture. White band at left was produced by cold-work of shearing along tubular surface of fracture. Part of tensile fracture is shown across top

M27228-2

(8x)

DPH (100-g load)

<u>Line A</u>	<u>Line B</u>	<u>Wire C</u>
446	450	437
454	454	464
433	464	454
454	473	
464	459	
429	446	
437	454	
454	454	
383		
433		
454		
420		
425		

Fig. 19. Microstructure and microhardness

DPH (200-g load, by lines)

A → B	D → B	E → B	C → B	R → B	S → B
549	540	512	528	512	466
593	584	509	549	516	516
593	549	532	544	528	532
589	557	528	505	509	528
575	544	532	540	532	516
575	566	473	549	579	516
549	566	549	589	579	520
544	570	524	579	566	549
553	557	528	516	584	557
584	549	553	509	575	584
		575	575		

Fig. 20. Microhardness. For DPH range, R_c hardness range is 49 to 54

Reassessment of the heads and seats disclosed two pronounced indentations in the surface of the seat adjacent to the wire hole. These were immediately traced to the rather large gripping-die flash shown undeformed in Fig. 14. It may be seen from Fig. 15 that when subjected to an ultimate tensile load, the flash was severely deformed by the seat. At the same time, forces on the bearing surface deformed the buttonhead, U in Fig. 21. Normally, such deformations are not apparent following a tensile test of a buttonhead with small flash. In addition, it was noted that in this kind of buttonhead failure, a large split was usually oriented at a wide angle from the plane of the flashes.

It was concluded from the investigation that when a 1.5FS Mk 1 buttonhead on Thermalized wire has large flashes, an unbalanced stress field forms in the head during a tensile loading. If that field is operating in conjunction with the notch created by a severely split buttonhead, a premature failure of the head may occur. To substantiate the conclusion, WCS embarked on another test program.

M24708-2

(4x)

Fig. 21. Posttest buttonheads on Thermalized wire. Gripping-die flash (F) has been partially flattened by seat during test. At the same time the buttonheads were deformed by high-bearing loads (U). Slip malformations (S) seem to be unaffected by test

WCS TENSILE TEST PROGRAM

An extensive test program to gather statistical data with which to evaluate the buttonhead-ability of Thermalized wire was planned and conducted by WCS; the details are reported in Part VI of WCS Technical Report No. 6 (Ref. 6). Gulf General Atomic was primarily interested in the performance of 1.5FS Mk 1 buttonheads with controlled and with noncontrolled flash (see Figs. 14 and 22, respectively).

Eight coils of wire were sampled at 100-ft intervals; from each sample a 15-1/2 in. length was cut for a tensile specimen. Seat washers (also referred to as test blocks and test anchor hardware) with newly surfaced seats were placed on the specimen, which was then buttonheaded on one end with a controlled-flash head and on the other with a noncontrolled-flash head. The first 500 specimens were buttonheaded as coil groups; the last 300 specimens were buttonheaded by alternating coil groups. The tensile tests were performed using the WCS 1200-kip test machine with a platen travel rate of 1.5 in./min. The load at failure was obtained using a strain gage load cell in conjunction with a type MDX-8 digital readout manufactured by Transducers, Inc. Resolution of the load-measuring system was 20 lb, and the accuracy was 1% full scale, or 200 lb.

The results (see Table 2) showed that 10 of the 1600 buttonheads failed, 5 at loads below the GUTS of the wire (11.78 kip). All of the failures occurred in buttonheads with noncontrolled flash; typical examples may be seen in Figs. 23 and 24. Nearly all of the heads examined following the test exhibited split and slip malformations, the actual count of which is recorded in Table 2. Originally, the count was for each head, but the difference in number and severity between the buttonheads on opposite ends of a specimen was found to be insignificant, so the total count was finally recorded.

M26450-1

(9x)

M26449-1

(9x)

Fig. 22. Controlled flash. Two views showing what is considered a practical limit of minimum attainable flash

TABLE 2
SUMMARY OF TENSILE TESTS OF BUTTONHEADED THERMALIZED WIRE

Coil No.	Tests	Ultimate Load (kip)			Head Failure		Specimens Checked	Malformations	
		$\bar{X}$	σ	V-%	>GUTS ^(a)	<GUTS		Slips	Splits
50/374/67	100	12.41	0.197	0.016	0	0	70	122	22
50/371/67	100	12.74	0.168	0.013	0	0	66	115	13
50/368/67	95	12.44	0.150	0.012	2	3	64	136	35
50/369/67	99	12.28	0.224	0.018	1	0	64	123	13
50/372/67	99	12.25	0.268	0.022	0	1	66	122	11
50/373/67	99	12.35	0.251	0.020	1	0	62	85	17
50/365/67	94	12.45	0.219	0.017	0	0	58	105	22
50/366/67	98	12.43	0.215	0.017	1	1	56	106	15

(a) GUTS - guaranteed ultimate tensile strength.

M25891-1

Specimen 247A

(3x)

M25897-1

Specimen 278A

(3x)

Fig. 23. Typical tensile test buttonhead failures showing the fracture and washer seat surface, Specimens 247A and 278A

M25900-1

Specimen 233A

(3x)

M25892-1

Specimen 234A

(3x)

Fig. 24. Typical tensile test buttonhead failures showing the fracture and washer seat surface, Specimens 233A and 234A

The obvious conclusions were that buttonheads on Thermalized wire must be made with a minimum flash (Fig. 22) and that the malformations were not the primary cause of buttonhead failure. Using the new criterion for flash, several full-size test tendons were prepared as part of another test program and subjected to relaxation tests without suffering any buttonhead failures.

FATIGUE TEST PROGRAMS

The design of the WCS 1.5FS Mk 1 buttonhead was a significant change from the widely used BBR buttonhead design. Since relatively little tensile and fatigue test data and only limited PCRV service experience were available, it was essential that some tests be performed to demonstrate the capabilities of the WCS buttonhead. The test program was actually designed to determine the tensile properties of buttonheaded wire specimens after subjecting them to fatigue loads.

The first test program was run using U.S. Steel Company SR wire and the second using RJ&N Thermalized wire. In both instances the test specimens were prepared by WCS (Ref. 6). Tests of the SR wire were conducted by the U.S. Steel Company Laboratory (Ref. 7); the Thermalized wire tests were conducted by the RJ&N Group Laboratory (Ref. 8). The test specimen with washer seat fittings is shown in Fig. 25.

The fatigue loads for both test programs were applied using Amsler High-Frequency Vibrophore machines. Both tests were run at a frequency of 6500 cpm.

The identical test programs consisted of five groups (designated Series 1 through 5) of seven test specimens. The following tests with the arbitrarily selected fatigue-test parameters were prescribed as follows:

Series 1	Static tensile tests of wire without buttonheads.
Series 2	Static tensile tests of wire with buttonheads.
Series 3	Postfatigue tensile tests of buttonheaded wire after 10-million cycles at $0.6 \text{ UTS} \pm 15 \text{ ksi}$.
Series 4	Postfatigue tensile tests of buttonheaded wire after 2000 cycles at $0.6 \text{ UTS} \pm 15 \text{ ksi}$.
Series 5	Postfatigue tensile tests of buttonheaded wire after 100,000 cycles at $0.6 \text{ UTS} \pm 3 \text{ ksi}$.

Fig. 25. Typical fatigue test specimen with washer seat fittings (courtesy of WCS)

All of the specimens were first stressed at 0.8 UTS for 2 min and then the load was reduced to 0.6 UTS for the cyclic loading. The number of cycles on the Series 4 and 5 specimens was estimated by timing the test machine.

Both the stress-relieved and Thermalized wire conformed to the requirements of ASTM A421. The wire chemistry and tensile properties (Series 1 tests of nonbuttonheaded wire) are shown in Tables 3 and 4.

TABLE 3
CHEMICAL COMPOSITION (WT-%) OF FATIGUE TEST WIRES

	C	Mn	P	S	Si	Sn	Cu
ASTM A421	<u>0.72</u> 0.93	<u>0.40</u> 1.10	0.040	0.050	<u>0.10</u> 0.35	---	---
Stress Relieved:	0.83	0.65	0.010	0.019	0.23	0.0	0.03
Thermalized							
Group I tests:	0.75	0.63	0.017	0.033	0.17	---	---
Group II tests:	Random wire conforming to A421.						

TABLE 4
TENSILE PROPERTIES OF NONBUTTONHEADED WIRE

	UTS (ksi)	TYS ^(a) (ksi)	Elong. (% in 10 in.)
ASTM A421 BA	240	192	4.0
Stress-relieved (avg of 7)	255.7	225.4	5.2
Thermalized (avg of 7)			
Group I Tests	254.0	232.0	5.4
Group II Tests	255.7	236.8	5.8

(a) At 1% total extension.

The SR wire specimens were prepared from bare, uncoated wire. The buttonheads were WCS 1.5FS Mk 1 (see Fig. 8). The Thermalized wire specimens were prepared by phosphating the wire using Metabond coating with Rustarest (Ref. 2) and buttonheaded initially using the WCS 1.5FS Mk 1 style with a noncontrolled flash.

Shortly after these specimens were prepared, several buttonhead failures occurred on a test tendon. The peculiar tubular shape of the failure was attributed to gripping-die flash on the bearing seat surface of the buttonhead. As a result of the failure analysis, additional fatigue test specimens were buttonheaded with controlled-flash heads at one end and with the more common noncontrolled flash at the other (see Series 6).

The test results for the SR wire indicated that the tensile properties of the buttonheaded specimens were not degraded by the fatigue loadings. Two specimens did fail during the fatigue loading, one in the wire after 3.5-million cycles, the other in the buttonhead after 4.7-million cycles. The data are recorded in Table 5.

The tensile properties of the Thermalized wire specimens were likewise unaffected by the fatigue loadings although 5 of the 7 specimens for Series 3 failed after less than 2-million cycles (see Table 6). These failures reportedly occurred at the fillet of the buttonhead.

The Series 3 tests of the Thermalized wire were repeated twice as Series 6 and 7. The Series 6 tests had to be conducted with only one buttonhead when it became necessary to remove a washer that had been put on the wire with the seat surface facing away from the buttonhead. Two specimens failed during the fatigue loading. One failed by fretting between the wire and washer about 1 in. from the buttonhead; the other failed at the buttonhead, and was attributed to erratic operation of the test machine. The postfatigue tensile properties were not degraded by fatigue although one buttonhead popped off at 233.5 ksi. The fracture

TABLE 5
POSTFATIGUE TENSILE PROPERTIES OF BUTTONHEADED SR WIRE

Series and Specimen No.	Specified Fatigue Test Reqs.	Total Cycles ^(a)	Tensile Properties		
			UTS (ksi)	TYS ^(b) (ksi)	Elong. (% in 10 in.)
2-1	None	---	255.4	224.2	5.6
-2			255.8	226.1	5.5
-3			255.4	225.1	5.6
-4			255.0	226.1	5.0
-5			256.2	226.1	5.4
-6			255.0	226.1	4.9
-7			255.0	226.1	5.0
Avg			255.4	225.7	5.3
3-A	10 ⁷ cycles at 0.6 UTS ± 15 ksi (138 to 168 ksi)	10,045,000	254.6	226.1	4.6
-B		3,504,000	(c)		
-C		4,681,000	(d)		
-D		10,106,000	255.6	228.1	5.2
-E		10,202,000	252.5	226.1	5.8
-F		10,078,000	253.6	226.1	5.2
-G		10,102,000	253.6	226.1	5.6
Avg			254.0	226.5	5.3
4-A	2000 cycles at 0.6 UTS ± 15 ksi (138 to 168 ksi)	3500	256.2	230.2	5.0
-B		2000	255.0	228.2	5.0
-C		1500	255.0	230.2	---
-D		2000	256.6	230.2	5.8
-E		2000	254.6	230.2	---
-F		2000	255.8	231.2	---
-G		1500	255.4	230.2	4.8
Avg			255.5	230.2	5.2
5-A	10 ⁵ cycles at 0.6 UTS ± 3 ksi (150 to 156 ksi)	105,000	256.2	232.2	5.5
-B		100,000	257.0	232.2	---
-C		100,000	256.2	232.2	5.4
-D		100,000	255.4	230.2	5.7
-E		100,000	256.2	230.2	5.8
-F		100,000	255.4	231.2	5.3
-G		101,000	256.6	232.2	5.3
Avg			256.2	231.5	5.5

(a) For Series 4 and 5, number of cycles measured by timing machine operation.

(b) At 1% total extension.

(c) Fatigue failure in wire.

(d) Fatigue failure of buttonhead.

TABLE 6
POSTFATIGUE TENSILE PROPERTIES
OF BUTTONHEADED THERMALIZED WIRE (GROUP I TESTS)

Series and Specimen No.	Specified Fatigue Test Reqts.	Total Cycles (a)	Tensile Properties		
			UTS (ksi)	TYS ^(b) (ksi)	Elong. (% in 10 in.)
2-A	None	--	255.0	234.0	5.6
B			253.5	231.0	5.1
C			252.0	231.5	5.5
D			253.5	231.5	5.2
E			254.0	234.0	5.3
F			254.0	234.0	5.3
G			255.0	234.5	5.2
Avg			253.7	233.5	5.3
3-A	10 ⁷ cycles at 0.6 UTS $\pm$ 16 ksi (138 to 170 ksi)	10,001,000	253.5	229.5	6.0
B		1,201,000	(c)		
C		18,948,000	253.5	219.0	5.3
D		1,517,000	(c)		
E		212,000	(c)		
F		269,000	(c)		
G		756,000	(c)		
Avg			--	--	--
4-A	2000 cycles at 0.6 UTS $\pm$ 16 ksi (138 to 170 ksi)	2500	256.5	233.0	6.0
B		2300	253.0	229.0	5.3
C		2300	254.5	231.5	6.5
D		2300	254.5	231.0	5.5
E		2300	253.0	229.5	5.0
F		2300	255.0	231.5	5.3
G		2300	251.5	229.5	6.3
Avg			254.0	231.0	5.4

TABLE 6 (Continued)

Series and Specimen No.	Specified Fatigue Test Reqts.	Total Cycles(a)	Tensile Properties		
			UTS (ksi)	TYS(b) (ksi)	Elong. (% in 10 in.)
5-A	100,000 cycles	104,000	254.0	229.5	5.5
B	at	104,000	253.0	229.5	5.8
C	0.6 UTS $\pm$ 4 ksi	104,000	250.5	228.0	6.0
D	(150 to 158 ksi)	104,000	253.5	231.0	5.6
E		104,000	254.5	232.0	5.2
F		104,000	253.5	229.5	6.0
G		104,000	254.0	229.5	6.5
Avg			253.5	229.5	5.6
6-A	10 ⁷ cycles	10,349,000	253.8	233.0	5.6
B	at	7,788,000	(c)		
C	0.6 UTS $\pm$ 16 ksi	10,001,000	253.0	231.2	5.5
D	(138 to 170 ksi)	10,249,000	233.5 ^(d)	231.2	--
E		2,068,000	(c)		
F		10,001,000	253.3	232.1	5.0
G		10,002,000	253.5	233.0	5.2
Avg			249.4	232.1	5.3
7-A	10 ⁷ cycles	18,000	(e)		
B	at	18,000			
C	0.6 UTS $\pm$ 16 ksi	18,000			
D	(138 to 170 ksi)	18,000			
E		2,500,000			
F	(Low flash buttonheads)	10 ⁷	--	--	--

(a) For Series 4 and 5, number of cycles measured by timing machine operation.

(b) At 1% total extension.

(c) Fatigue failure in wire or buttonhead, in Series 3 the static tensile properties of the broken specimens were tested and reported by RJ&N (GL 68/3/15).

(d) Buttonhead tubular failure.

(e) Five of the six specimens failed in the buttonheads, sixth specimen not tested for tensile properties.

revealed no evidence of fatigue damage, but a buttonhead split penetrated the fracture area and is believed to have contributed to the premature failure.

The Series 7 specimens were made with controlled-flash heads on both ends. Five of the six specimens failed in the buttonhead during the fatigue loading. Metallurgical examinations of these heads only revealed zones of a severely cold-worked microstructure probably caused by the severity of the upsetting operation to make the Mk 1 buttonheads.

A new set of specimens, Group II, was prepared and the entire test program was repeated. The samples were randomly selected from production coils of 0.250-in. Thermalized wire but the heat numbers, hence chemical analyses, are not known. The data, recorded in Table 7, show that none of the specimens failed during the fatigue loading, and that the tensile properties of the wire were not degraded. In addition to the required tests, RJ&N elected to continue the 138 to 170 ksi fatigue loading of some extra specimens. The exact number of specimens so tested is not known, but all of them are reported to have survived between 40-million and 100-million cycles. The fatigue fractures occurred across the base of the head.

It was concluded from the fatigue test programs that the wire and buttonheads did not experience degradation of tensile strength when subjected to the specified fatigue loadings.

TABLE 7
POSTFATIGUE TENSILE PROPERTIES OF BUTTONHEADED THERMALIZED WIRE
(GROUP II TESTS)

Series and Specimen No.	Specified Fatigue Test Reqts.	Total Cycles ^(a)	Tensile Properties		
			UTS (ksi)	TYS ^(b) (ksi)	Elong. (% in 10 in.)
2-A	None	--	261.0	238.0	5.5
B			258.0	235.0	5.0
C			249.0	219.0	6.0
D			261.0	239.0	5.5
E			261.0	242.0	5.0
F			260.0	233.0	5.0
G			248.0	216.0	6.0
Avg			256.8	231.7	5.4
3-A	10 ⁷ cycles at 0.6 UTS ± 16 ksi (138 to 170 ksi)	>10 ⁷	256	233	5.6
B			254	229	5.5
C			253	227	5.1
D			255	235	5.6
E			253	227	5.6
F			255	225	4.8
G			255	233	5.1
Avg			254.4	229.8	5.3
4-A	2000 cycles at 0.6 UTS ± 16 ksi (138 to 170 ksi)	≥2000	254	233	4.5
B			256	229	5.4
C			255	230	4.7
D			254	231	4.5
E			255	229	5.5
F			255	233	5.1
G			254	232	4.4
Avg			254.0	232.0	4.9
5-A	100,000 cycles at 0.6 UTS ± 4 ksi (150-158 ksi)	≥100,000	262	243	4.6
B			261	241	5.1
C			259	236	4.7
D			253	227	4.5
E			257	237	5.1
F			255	231	4.6
G			250	218	4.8
Avg			256.7	233.6	4.8

(a) Total cycles not reported by RJ&N.

(b) At 1% total extension.

BUN-BISCUIT BUTTONHEADS

Gulf General Atomic notified RJ&N of their concern over the slip and split imperfections. Samples with these imperfections and some of the early test failures were sent to them for their analysis and recommendations for corrective action. They undertook an extensive investigation, the results of which were reported to WCS by RJ&N's Group Laboratory (Ref. 9). Splits were conceded to be caused by imperfections in the wire; further discussion of splits is deferred to another section of this report.

The RJ&N staff called attention to the discontinuity of the head shape, which they descriptively referred to informally as the bun-biscuit shape and which GGA later identified as a ring-ridge condition. Several examples of the condition are shown in Fig. 26. The bun, or top portion, of the head obviously conformed to the shape of the upset-die cavity; the biscuit or bottom portion of the head appeared to have been caused by a radial displacement of the upset wire that was pinched between the gripping and upsetting dies. In many instances the slip imperfections were confined to the biscuit.

In the words of RJ&N staff members, "Thermalized wire, because of its peculiar [unique] properties, shows a tendency, under compressive loading, to deform by shear rather than uniform plastic flow." They also suggested that with the 1.5FS buttonheads, such movement is unimpeded; i.e., the buttonhead starts to deform sideways until it is stopped by the die and then during the final movements of the upsetting die, it is pushed to the opposite side to fill the die cavity. This gives rise to a plane of heavily slipped metal.

They also made tests wherein cubes cut from Thermalized wire were "forged" along all three mutually perpendicular axes. These tests showed the material to deform much more easily in a transverse rather than axial direction, as

M26154-1

(4x)

M26154-2

(4x)

Fig. 26. Examples of 'bun-biscuit' buttonheads. The top left buttonhead has a perfect shape; others exhibit ring-ridge and slip imperfections

would be expected in a material where the properties have been preferentially developed to a high order in one direction, i.e., longitudinally.

This information, combined with the GGA idea that less metal should be upset to form 1.5FS heads on Thermalized wire, led to another statistical tensile test at RJ&N.

RJ&N TENSILE TEST PROGRAM

When RJ&N received a WCS buttonheading machine (to be used for quality control tests on production wire) they were able to experiment with its adjustments to make improved buttonheads on Thermalized wire. It was found that if less wire was upset, few imperfections appeared in the buttonhead and the bun-biscuit shape was virtually eliminated. Normally, WCS indexed approximately 0.50 in. of SR wire to be upset. By decreasing the index to 0.42 in., the head height was reduced, but the other dimensions were essentially unchanged. Nevertheless, since a major change in a dimension was being proposed, GGA required that at least 1000 buttonheads of the new design be tested to demonstrate the acceptability of the modification.

The report of the test results (Ref. 10) from RJ&N can be summarized by saying that of 1100 modified buttonheads tested, only two failures occurred. These two failures were attributed to nonuniform loading from a badly deformed seat on the washer nut. The test specimens represented the first 12 coils of wire produced for Fort St. Vrain plus 6 coils that had been produced earlier as a part of the trial shipment to WCS, but which had been rejected due to rolling defects. The 6 coils had been tested with 1.5FS Mk 1 heads and had resulted in about 4% head failure. With the modified buttonhead, no failures occurred in 218 tests.

The modified buttonhead, designated as the 1.5FS Mk 2 buttonhead (Fig. 27) was accepted for use on the tensile test specimens representing the production coils of Thermalized wire for Fort St. Vrain.

1. HEAD ECCENTRICITY: 0.030 IN.
MAX TOTAL INDICATED READING

2. SEAT ECCENTRICITY: 0.015 IN.
MAX TOTAL INDICATED READING

Fig. 27. WCS 1.5FS Mk 2 buttonhead. This head differs from Mk 1 in that head height has been reduced to 0.235/0.265 in. from 0.280 ± 0.020 in.

WCS SHOP-FABRICATED BUTTONHEADS

Difficulties with buttonhead size occurred again when WCS started fabricating tendons to meet the Mk 2 buttonhead requirements. If they set the machine to index 0.42 in. of wire for upsetting, dimensional checks using an optical comparator revealed that head height and diameter were within tolerance, but the bearing surface diameter was fractionally undersize. On the other hand, if more wire was indexed to get the proper bearing surface diameter, a bun-biscuit head was formed. The dilemma was resolved by another test program in which 1000 buttonheads with a reduced bearing surface diameter were subjected to an ultimate tensile load test.

The bearing surface diameter was arbitrarily limited to 0.330 in. min, but was allowed to vary between 0.330 and 0.335 in. with the provision that upon successful completion of the test, the GGA specification limit would be established at 0.335 in. min. Three coils of Thermalized wire were each represented by approximately 330 specimens buttonheaded on both ends. Before being tested, the buttonheads on every tenth specimen were checked, using an optical comparator, for head diameter and height and seat diameter. Following the test, nearly all of the heads were examined for imperfections.

The test results, summarized in Table 8, indicated that the bearing surface diameter could be reduced to 0.335 in. min without sacrificing any of the load-carrying ability of the buttonhead. Although seven heads failed, based on the previous definition of a failure, only one tubular-type failure occurred, and the rest occurred in the wire within 1/4 in. of the head. Note that for two of the coils less than 1/4 of the heads exhibited slip imperfections. Virtually all of the heads were formed without the ring-ridge condition.

TABLE 8
SUMMARY OF PERFORMANCE TESTING WCS 1.5FS Mk 3 BUTTONHEAD

Coil No.	No. Specimen Heads	Head Failures ^(a)	Inspections				Measurements (in.) ^(b)		
			No.	Sound	Slips	Splits	D	H	d
8/207/69	330 660	0	655	402	190	78	0.381- 0.390	0.255- 0.260	0.330- 0.337
6/1795/69	330 660	5	657	61	257	445	0.379- 0.390	0.242- 0.265	0.330- 0.342
6/1793/69	340 680	2	677	437	2	239	0.382- 0.389	0.245- 0.255	0.331- 0.335

(a) In or within 1/4 in. of head.

(b) D = head diameter, H = head height, and d = bearing surface diameter.

Based on these results, the 0.350 in. min bearing surface diameter was changed to read 0.335 in. min in the GGA specifications and the new buttonhead was designated as the 1.5FS Mk 3. (See Fig. 28.) As such it was used on all tendons fabricated for the Fort St. Vrain PCR.V.

1. HEAD ECCENTRICITY: 0.030-IN.
MAX TOTAL INDICATED READING

2. SEAT ECCENTRICITY: 0.015-IN.
MAX TOTAL INDICATED READING

Fig. 28. WCS 1.5FS Mk 3 buttonhead. This head differs from Mk 2 in that bearing surface diameter has been reduced from 0.350 in. min to 0.335 in. min

WIRE PREPARATION FOR BUTTONHEADING

As noted previously, buttonheads on Thermalized wire were more prone to malformations than the domestic SR wire. The higher pressure needed to upset the wire to form a buttonhead suggested that the wire had less plasticity or formability. In addition, it was often evident that the wire did not shear (cut) as cleanly as the SR wire. We therefore considered the possibility that the shear-cut might be a factor contributing to the malformed buttonheads.

To evaluate the effects of wire-end preparation, 25 samples were sheared from each of three coils of Thermalized wire. One end was then recut with a water-cooled abrasive wheel. The remaining sheared end of each sample was measured to determine the maximum deviation from square; the results are shown in Table 9.

TABLE 9
SHEAR CUT WIRE

Coil No.	No. of Wires	Deviation from Square (in.)	
		Avg.	Range
50/365/67	29	0.0073	0.001 - 0.011
50/368/67	24	0.0043	0.002 - 0.006
50/371/67	27	0.003	0.001 - 0.005

The samples were identified for the buttonheading operation and then selected using a random-number table. The ends of the selected sample were buttonheaded in sequence using the standard WCS hydraulic machine adjusted to produce the WCS 1.5FS Mk 1 buttonheads. Each buttonhead was

then examined macroscopically to determine the number of malformations for each head. These data arranged by coil number are summarized in Table 10.

TABLE 10
BUTTONHEAD CONDITIONS

Coil No.	No. of Heads	Cut End			Sheared End		
		None	Slips	Splits	None	Slips	Splits
50/365/67	58	9	15	11	8	17	9
50/368/67	48	7	13	6	3	18	7
50/371/67	54	2	21	11	5	18	8

If the buttonheads contained both slip and split malformations, a tally was made in each column. The data indicated that there was little, if any, difference between the cut-end and sheared-end buttonheads; typical examples of the heads are shown in Fig. 29.

The RJ&N staff reported that during their statistical tensile tests of the Mk 2 heads, they found it necessary to cut the wire with a bolt cutter. Contrary to the belief that wire had to be cut square, their confidence in the ability of the wire and the WCS buttonheading machine to make good buttonheads on such poorly prepared wire was vindicated because none of the heads failed.

The GGA specification for tendon installation permitted rebuttonheading provided the defective buttonheads were individually removed using a carbide-disk cutter. On full-size test tendons this was done successfully, although many of the wire ends exhibited temper colors because of the heat generated just prior to severance of the wire. Nevertheless, none of the heads subsequently formed on the abrasively cut wires failed when the tendon was tested to ultimate load.

Another instance where abrasive cutting became necessary arose when eccentric heads (Fig. 30) were inadvertently produced on two vertical tendons (VI 6 and VI 11) of the Fort St. Vrain PCRV. From cursory field tests, it was found that overheating could be prevented by frequently replacing

M26355-1

(2.5x)

M26356-1

(2.5x)

Fig. 29. Sheared versus cut wire buttonheads. Typical examples representing the three coils show buttonheads on opposite ends of same wire; cut-end, top, and sheared end, bottom

M32385-4

(2.5x)

Fig. 30. Eccentric buttonheads. Field buttonheads on tendons VI 6 and VI 11 were eccentric, left; center and right buttonheads were made of test specimens. Note ring ridge (arrow), which is cause for rejection

the cutter and by water cooling. Some temper color, however, was always evident at the point of severance. As a criterion for an acceptable cut, visible temper color on the surface of the wire was arbitrary limited to one-half the wire diameter from the cut end. Some examples of cut ends are shown in Fig. 31; the buttonheads formed on similar cuts are shown in Fig. 32. Twelve samples with cut ends exhibiting the limit of temper color were buttonheaded and tensile tested. None of the heads failed or showed evidence of deformation resulting from a wire softened by cutoff heat.

Subsequent metallography revealed that the acceptance criterion was conservative (Fig. 33).

M32385-8

(2.5x)

Fig. 31. Abrasively cut wire. Wires cut with a carbide disk exhibit a temper color. Cuts on left and center wire are acceptable; cut on right is unacceptable

M32385-6

(2.5x)

Fig. 32. Buttonheads formed on abrasively cut wire. Buttonheads produced on corresponding (above) carbide-cut wires supported ultimate tensile strength of wire

M32385-9

(100x)

Fig. 33. Microstructure of abrasively cut wire. Transformation occurred near point of severance, and surface microstructure adjacent to cut was tempered slightly, but subsurface structure was essentially unchanged

TENDON FABRICATION

Investigations of buttonheading and the effects of imperfections and malformations continued during tendon fabrication, primarily in the interest of quality assurance.

A unique slip imperfection was found in a test sample buttonhead. It was unusual in that the slip intersected the bearing-seat surface as shown in Fig. 34. Even though it was considered a severe condition, the head survived a tensile load test. The photograph also shows what is considered to be a small gripping-die flash, and a small wart on the bearing surface caused by a chip in the gripping die. The wart and slip malformations as shown are considered to be undesirable but acceptable.

On another occasion, tendon fabrication was stopped to replace a gripping die when a severe wart was found on the bearing surface (Fig. 35). While a wart of this size is intolerable on a split head, it did not cause a failure of a tensile specimen buttonhead on this coil of wire.

Only two coils out of a total order of 1700 coils were rejected during tendon fabrication because of split malformations. The one that occurred on coil No. 39/19/69 caused failure of the buttonhead (Fig. 36). The flash on this head was marginal because its profile was large, although thin in section. When this condition was revealed by the tensile test conducted before each coil was used, a sample was taken from the opposite end of the coil; the buttonhead formed was perfect (Fig. 36), illustrating the point that splits are caused by discontinuous imperfections in the wire. Splits, in fact, seem always to be associated with seams or laps in the wire.

Fig. 34. Slip-malformation. This slip is unusual since it opened the bearing seat surface. Arrow (a) indicates gripping-die flash. Arrow (b) indicates a wart formed by a chipped gripping die

M32385-5

(2.5x)

Fig. 35. Wart malformation. Left buttonhead exhibits excess metal (wart) on bearing surface caused by a chipped corner on gripping die. Right buttonhead was made with a new die

M32385-7

(3x)

Fig. 36. Split buttonhead on tendon wire. Leading end of coil 39/19/69 split badly and failed a tensile test - coil was rejected. Trailing end of wire formed good buttonheads. Top view shows broken head and size of split

WIRE SEAMS

During fabrication of another tendon at WCS, severely split buttonheads were observed to occur on wire taken from coil No. 8/237/69. The test sample taken at the start of this coil had produced satisfactory buttonheads, which had supported the ultimate strength of the wire. As wire from this coil was laid up in the tendon, splits were observed in the buttonheads from as many as ten of the cut lengths of wire.

Since the wires were mixed with those from another coil, no sequence of occurrence was established, but all wire exhibiting a buttonhead similar to the one shown in Fig. 37 was rejected and removed from the tendon. In most instances such buttonheads were badly deformed as a result of the split and would have been rejected for oversize diameter, discontinuous contour (bun-biscuit condition), and discontinuous seat surface.

In addition to asking the quality-assurance surveyor in England for information about wire seams, samples of the coil were examined metallographically at GGA to obtain first-hand information on the condition causing the split. The surface prepared for examination was essentially tangent to the wire at a point having the same orientation as the split. The condition observed is shown in Fig. 38. Another piece of the wire, examined macroscopically, disclosed the seam in the wire surface. (See Fig. 39.)

A cross section of the wire revealed the seam and the adjacent partially decarburized microstructure. Microhardness measurements were made to show the relative hardness of the wire and decarburized zones (Fig. 40).

Gulf General Atomic's surveyors, British Engine Insurance Co., Ltd. (Ref. 11), reported, "... that splits in buttonheads may be associated with the metallurgical condition of the wire. We have sectioned wires immediately below the splits in a number of cases and from microscopic examination,

M30818-1

(7x)

Fig. 37. Severely split buttonhead, RJ&N Thermalized wire, coil No. 8/237/69

M30819-2

(250x)

M30819-1

(250x)

Fig. 38. Metallography of a seam. Two longitudinal views of seam and decarburized microstructure. Polished surface is nearly tangent to wire

M30818-3

(8x)

M30818-2

(16x)

Fig. 39. Seam macroscopy. Two views of seam (arrows) in wire causing split buttonhead

M30818-5

(250x)

1	183 DPH	(7) R_c
2	370 DPH	38 R_c
3	478 DPH	47.5 R_c
4	478 DPH	47.5 R_c

Fig. 40. Transverse section of seam. A section of wire showing seam and associated decarburization (microhardness measurements - 100-g load)

these splits arise at either surface oxide inclusions or metal folds or both, and these we feel may be generated during the rod rolling process. As billets are flame dressed and acid dipped, we assume the oxide has arisen from the subsequent heating at rod rolling. There is, so far, no evidence of any other cause for the splits associated with the wire itself."

They further reported that during a 3-month period, some 56,000 buttonheads had been made on 0.276-in. (7mm) diameter wire and the rejection rate (based on 1/16 in. total split width per head) was approximately 0.5%. "Tensile tests on split buttonheads indicate that these do not affect the ultimate tensile failure either in the load or position of rupture. It is not our experience ... that splits produced during button-heading extend into the undeformed wire."

A buttonhead "exhibiting considerable splitting" survived a tensile load test -- the wire failed 7 in. from the head. Figure 41 shows the split buttonhead and "... at two positions (on a metallographic section) a folding in of the material, presumably during rod-rolling with evidence of oxide inclusions in one fold."

GGA continued investigating split buttonheads in an effort to establish a realistic rejection criterion for the relatively few instances of severely split heads.

Seams that cause severe splits are normally detected in the rod stock and rejected for prestressing wire by the wire manufacturer. If there is doubt about the rod condition, a short length may be upset to observe the action of the suspected seam. An example of a rejectable rod seam and its appearance in an upset slug are shown in Fig. 42. Occasionally, an undetected rod seam will be passed and later will appear in a buttonhead on the finished wire. To illustrate, the wire manufacturer sent GGA samples of splits in a tulip-shaped buttonhead (Fig. 43). Their local customer has a rejection criterion that the total width of such splits per head shall not exceed 1/16 in. The large split was considered to be marginal. Severe splits in tendon wire buttonheads have been shown throughout this report; two more

(6x)

Fig. 41. Split buttonhead on 7 mm wire. Insert shows "folds" in wire
(courtesy BE)

M31379-7

(3.5x)

Fig 42. Rod seams. If billets are not properly scarfed, a seam may occur in rod. When a short section is upset, split shown at left above occurs. This rod sample was deep-etched to reveal seam

M31379-4

(4x)

Fig. 43. Splits in tulip-shaped buttonheads. Deep etching wire sample revealed the seam that produced split. Cause for small split was not determined

examples are shown in Fig. 44 as they appeared in 1.5FS Mk 3 buttonheads. Their appearance seemingly warrants rejection of the wire, but these buttonheads did not fail during a tensile test.

To see just how severe a split needed to be to cause a buttonhead failure, tensile test specimens of that coil were buttonheaded using a machine set to make 1.5FS Mk 1 heads on Shinko SR wire. The buttonheads on the Thermalized wire were done as a bun-biscuit type exhibiting both slip and split malformations. Some splits were then exaggerated by cutting radially into the head from both sides with a hacksaw; the cuts, however, did not join at the top of the head (Fig. 45). When tested, the heads supported the ultimate load on the wire.

Next some splits were enlarged by cutting diametrically across the top of the head (Fig. 46). Again the heads supported the ultimate load. More heads were cut even deeper across the top until tubular failures were obtained in the two heads shown in Fig. 47. Apparently sufficient metal had finally been removed from the center of the head to allow the slot to collapse, causing a tensile fracture to initiate near the midpoint of the head. The fracture enlarged radially until the circumferential shear surface would no longer support the load, and the wire pulled out of the head to form a tubular failure.

It was concluded from this series of tests that rather large splits could be tolerated, provided that they did not bisect the head and that they were not operated on by unbalanced forces caused by excessively large flash and warts as previously discussed.

M31379-6

(3.5x)

Fig. 44. Splits in 1.5 FS Mk 3 buttonheads. One good and two split buttonheads recently produced on RJ&N Thermalized wire. When tested by a tensile load, failure occurred in wire

M31379-3

(4x)

Fig. 45. Artificial splits, radially cut. Two saw cuts exaggerated splits, but this head did not fail when subjected to ultimate tensile strength of wire

M31379-5

(4x)

SHADED AREA SHOWS
EXTENT OF SAW CUT

Fig. 46. Artificial splits diametrically cut. This head was sawed across the top to form an extreme split condition; when tested it failed in wire 2.75 in. from this head

M31379-1, -2

(4x)

Fig. 47. Artificial splits causing buttonhead failures. The left head shows the remains of a natural split. In the sketches below, shaded area shows extent of saw cut; dotted line shows fracture and shear surface

PRODUCTION WIRE BUTTONHEADS

Midway in the production of wire, the quality-assurance surveyor, British Engine Insurance, Ltd., was asked to obtain samples of buttonheads produced on wire test samples at RJ&N. We were interested to see the size, shape, and general condition of the buttonheads being tested to qualify the wire. The samples shown in Fig. 48 represent 6 coils of wire (3 heats of steel) produced during the 39th, 40th, and 41st weeks of 1969. It was reported that these buttonheads were considered typical for the wire being accepted and shipped.

The heads were similar in appearance to those being produced during tendon fabrication at WCS (Fig. 49). While GGA would have preferred wire free of seams, etc., that cause split imperfections, the wire and buttonheads complied with the requirements of the GGA specifications (Refs. 12,13). The tensile and bend properties of the wire were satisfactory and the stress relaxation, indicated to be 4% in 30 yr, was considerably better than the requirement of 8% max (Ref. 14).

9699
40/17/69

9699
40/16/69

9699
40/47/69

M31674-1

(3x)

2926
41/29/69

9179
39/17/69

9179
39/4/69

M31674-2

(3x)

Fig. 48. RJ&N tensile test buttonheads. Buttonheads represent three heats of steel and three weeks (39th, 40th, 41st) of wire drawing

M32385-3

(2.5x)

Fig. 49. WCS sample production buttonheads. Typical 1.5FS Mk 3 buttonheads produced on tendons during January and February 1970

CONCLUSIONS

The numerous tests and investigations reported herein have demonstrated the excellent capabilities of the WCS 1.5FS Head-Seat System. When used in conjunction with Thermalized wire, the Fort St. Vrain PCRV was provided with not only the positive wire anchorage needed for the unbonded tendons but also with a low stress-relaxation wire.

It has been shown that buttonheads consistently supported the ultimate tensile strength of the wire. In addition, that strength was not degraded by fatigue loadings far in excess of those needed for the dynamic design requirements of the tendons, which are only stressed at 70% GUTS of the wire.

The split imperfection in both SR and LR wire was caused primarily by laps and seams apparently rolled into the rod-stock, and drawn out as a fine, nearly invisible seam in the wire. When a buttonhead was made, the seams often ruptured to become an unsightly but essentially innocuous split.

Slip imperfections resulted from severe deformation of the wire during cold-upsetting to form a buttonhead. Thermalized wire, because of its highly oriented microstructural condition needed for its low stress-relaxation property, was particularly susceptible to this malady when formed into the somewhat larger 1.5FS Mk 1 buttonhead; however, slips were reduced to the point of insignificance by careful control of the wire index-setting on the machines used to make the slightly smaller 1.5FS Mk 3 buttonhead.

ACKNOWLEDGMENTS

The author wishes to thank all who conducted the many tests and examinations and contributed their findings to this report, including L. Gibbon, R. Stetson, N. Baker, and J. Knipping of GGA; A. Stubbs, H. Reuter, M. Caplan, M. Hazelton, and others at WCS; P. J. Hollingum at BE; and G. Sleigh at RJ&N.

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