LESSONS FROM SERIOUS INCIDENTS AT SEVEN ARCH DAMS

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Evolution of Arch Dam Design

Evolution of design of the modern arch dam may be divided into three phases:

Pre-1926:

Two-dimensional elastic arches were assumed to carry the entire load imposed on the dam. The constant angle arch concept used for over 30 dams in the US, is typical of this category. Typical examples of this generation are: Pacoima, CA, 372 ft. high and Diablo, WA, 389 ft. high; both were the highest arch dams in the world in 1928-29.

1926-1945:

Based on the 1926 test on the 60 ft. high Stevenson Creek experimental dam in California and on 1:12 scale structural models of the same dam, an extensive method of mathematical analysis, the three dimensional Trial Load Analysis (TLA) was developed by the US Bureau of Reclamation. Typical dams of this category are: Hoover, Hungry Horse, Glen Canyon and Yellowtail which range in height from 726 ft. to 525 ft.

1945-1965:

At the end of World War II, dam designers in France, Italy and Portugal reverted to the use of small scale structural models in preference to time-consuming mathematical calculations, such as the TLA. Typical dams of this era were much thinner than the earlier generations, and some had very high crest length to height ratio. Le Gage, Malpasset and Tolla dams represent the ultra thin dams of this genre.

Post 1965:

With the advent of fast digital computers and the Finite Element Method (FEM), most present day arch dams have double curvature and use higher design stresses. Koelnbrein, Zeuzier and El Fryle dams, discussed in this paper, belong to this generation.

Incidents at Seven Arch Dams

Pertinent data for the seven arch dams, where serious incidents occurred during 1955 to 1990, are shown in Table I. The incidents were:

Malpasset, France.

The dam suddenly failed in December, 1959, four years after first filling of the reservoir. The disastrous flood caused a loss of 440 lives.

Le Gage, France.

After the first filling of the reservoir in 1955, extensive cracking occurred on both faces of the dam and continued to progress for the next 6 years. After failure of Malpasset dam, Le Gage dam was abandoned and a new thicker arch dam constructed upstream.

Tolla, France.

The ultra thin arch dam was completed two years after failure of Malpasset. Upon first filling of the reservoir in 1961, extensive cracking appeared on the downstream face near the abutments of the upper half of the dam. Since cracking continued to progress, for the next 8 years, a new downstream arch and buttresses were built to strengthen the original arch.

El Fryle, Peru.

Located in a highly seismic area at an altitude of 4000 m, the thin arch dam was built in a U-shaped canyon. With the reservoir partially filled for the first time, there was a major slide in one of the banks resulting in loss of abutment support and most of reservoir storage. The arch dam itself did not collapse.

Koelnbrein, Austria.

Cracks and substantial leakage appeared in the lowest foundation gallery when the reservoir was 80 percent full two years after completion. Full uplift was also observed over the entire base of the central blocks. Major repair work costing US$85 million was undertaken during 1989-94 to restore the dam to a safe operating condition.

Zeuzier, Switzerland.

Twenty years after the dam was completed with reservoir nearly full considerable *upstream* movement of the dam occurred and 1.5 cm wide cracks appeared on the downstream face. The reservoir was lowered and extensive repairs were necessary.

Pacoima, California

In 1971 when the dam had been in service for 42 years, the San Fernando earthquake occurred. Maximum horizontal acceleration of 1.2 g was measured at the left abutment above the top of the dam. There was no structural damage to the arch itself, but the left abutment rock massif was destabilized and required extensive repairs. A second major incident, the Northridge earthquake of January 17, 1994, caused cracking in the left end block of the arch but did not significantly destabilize the previously strengthened left abutment rock mass. Maximum accelerations measured during the 1994 earthquake were: 2.3 g horizontal on top of the dam and 1.5 g horizontal and vertical at the left abutment near the crest of the dam and 0.5 g in all directions at the base of the dam.

Table I Pertinent Data for Seven Arch Dams

Dam	Max Hght. (ft.)	Year Built	Year Res. Filled	Year Incident	Incident
Le Gage	154	1954	1955	1955-63	Excessive progressive cracking.
Malpasset	218	1954	1954-59	1959	Disastrous failure of dam.
Tolla	295	1961	1961	1961-70	Excessive cracking.
Koelnbrein	656	1977	1977-78	1978	Cracking at base and high uplift pressures.
Zeuzier	558	1957	1960	1978	Major cracking due to abutment movement.
El Fryle	220	1961	1961	1962	Collapse of one abutment & loss of reservoir.
Pacoima	375	1929	1930	1971&91	Major earthquakes in close vicinity. Minor damage to dam. Major abutment instability.

The Thin Arch Dam Syndrome

Before analyzing the causes of, and lessons to be learned from the cited incidents, it is important to discuss the post-1945 developments in Europe in the field of arch dams. Before that date, design of high and large arch dams was dominated by the US Bureau of Reclamation, with the TLA method as the mathematical basis for stress analysis. A crude form of the modern day FEM analysis, the TLA was considered too laborious by many engineers.

In the early 1950s several European engineers published articles indicating that the USBR designs were too conservative and, as typical examples, compared the cross sections of Hoover, Hungry Horse and other dams against slender European dams. The influence of shape of the dam site and foundation characteristics was rarely discussed.

Reliance on small scale structural models in lieu of extensive calculations required by the TLA, was preferred by several European designers. Models were also preferred because various shapes of the arch could be checked and compared in a far shorter period than elaborate mathematical analyses.

Developments of this period gave birth to what may be called the *Thin Arch Dam Syndrome.* Some called arch dams "membranes", "flexible" or "thin shells" and several ultra thin arch dams were designed and built, among them Le Gage, Malpasset and Tolla in France. To compare the slenderness of arch dams, even a *Boldness Index* was proposed in 1953.

Typical symptoms of the *Thin Arch Dam Syndrome* may be found in the seminal paper "Arch Dams; Their Philosophy" by Andre Coyne in J. Power Division, ASCE, April 1956[1]. Mr. Coyne designed Le Gage, Malpasset and Tolla dams. The following quotations from this paper are illustrative of his mindset, and that of some other important arch dam designers of that era:

On ultimate failure of an arch dam:

> "Arch dams work as self-sealing plugs , becoming stronger and more taught as the thrust of the forces bearing down on them increases. In hard fact, the total and general crushing of their constituent materials is their only yield point."

Analysis of a failure test on a 10 ft. high structural model:

"Failure started where the arch was thicker than elsewhere and gradually extended, whereas in parts of normal thickness, the concrete worked at 4,300 psi without showing any *visible* signs of excessive strain. So the experiment revealed both the great strength of arches and drawbacks of any *awkwardly applied stiffening* which, far from strengthening structures, is a cause of weakness."

On models and TLA:

"...The best thing to do is to put up with *simplified* calculations, giving results within two limits and to get from them the *courage* for making up one's mind for choosing a given design."

"Present day applications are very different from those fashionable a few years ago, consisting in using models simply to confirm the correctness of the method of calculations."

"Today, *over-exacting calculations should they be necessary, particularly for calming the troubled consciences of a few people* are only undertaken as a final check, after all the dimensions have been established in the laboratory." [1,2]

The Coyne paper does not at all mention the great influence of foundation conditions on the stability of an arch dam. His observations on the performance of Le Gage dam after the reservoir was filled for the first time and some cracking occurred, are illustrative of the trend to play down the adverse impact of excessive foundation deformations:

"On filling of the reservoir the dam *foundations underwent very marked changes resulting from local subsidence* of the rock, of excellent quality on the whole. The distribution of stresses altered several times running and in some places *the concrete freed itself from excessive extension (tension) by cracking, without any serious consequences.*

"The more *daring, the thinner,* the more loaded the dam, *the greater the importance of local rock defects.'"*

Despite the warnings given by Karl Terzaghi[3] in his classic paper "The Role of Minor Geological Details on Safety of Dams", 1929, the importance of hydraulic uplift in the foundations and at the dam-rock contact was ignored by the thin arch dam advocates, and no foundation drainage systems were provided in several dams, including Le Gage, Malpasset and Tolla.

The quality of rock foundations suitable for thin arch dams was also studied extensively by Portuguese[4] engineers by experiments on small scale models. In the enthusiasm to justify thin arch dams, they came to the following conclusions:

"Arch dams are not as influenced by the deformability of their foundation as it is sometimes thought and so *can be founded on rocks with very low moduli of elasticity.*

"Variations of deformability have a strictly local influence on the state of stress in the dam and given their irregular distribution, they can *never be considered in the design.*

"For foundations with modulus = 1/7 of modulus of concrete the state of stress in the dam hardly changes."

While M. Rocha did stress the need to evaluate the influence of various geological defects on stability of the dam, the above cited conclusions encouraged some engineers to build thin arch dams on generally poor rock foundations, thereby increasing the risk to safety of the structure.

At the Sixth International Congress on Large Dams held in New York in 1958, several papers touted the economic advantages of very thin arch dams designed on the basis of tests on small scale models and claimed no sacrifice in safety, durability and performance. At that time the USBR felt much pressure for being old fashioned and not keeping up with the advances in Europe. Consequently, its Chief Design Engineer spent three weeks during the summer of 1959 visiting dams in Europe, and after the failure of Malpasset Dam in December, 1959, a three man team of USBR specialists visited 43 dams and several engineering organizations and laboratories in six European countries during August - October 1960. They inspected Le Gage Dam and the failed Malpasset dam[5].

Lessons from the Incidents

Le Gage Dam

A photo taken by USBR[5] engineers in September 1960 shows leakage through radial contraction joints and possibly through cracks and horizontal construction joints near the foundations. They agreed with the design engineers, (nine months after the failure of Malpasset dam), that *"the structure had the tendency to relieve itself of high stresses by cracking, without any serious effects."* However, the cracking continued to progress and the responsible authorities decided to abandon Le Gage dam and build a new thicker arch dam upstream in 1963. (Fig. 1).

The lessons are:

- The foundations for an arch dam should be properly treated by replacement of poor rock with concrete, grouting and drainage.
- Extensive and progressive cracking can seriously impair the safety and durability of a thin arch dam. A cracked dam is not as strong as an uncracked one.
- To reduce tensile stresses thicken the arch, particularly towards the abutments and the river bed.
- Provide interlocking keys in the contraction joints in all arch dams and grout them.

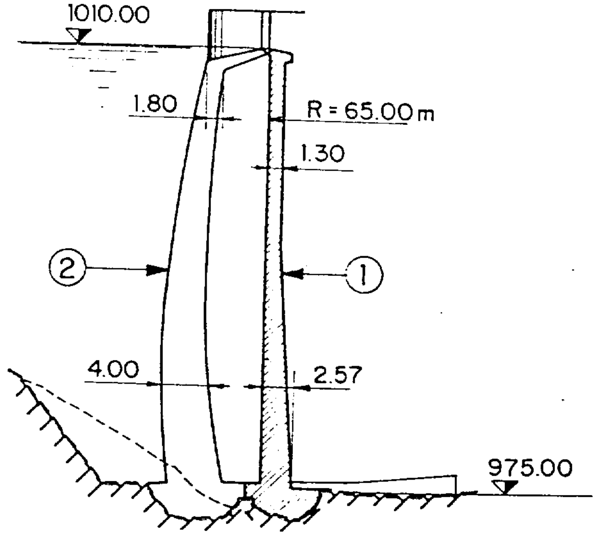


FIG 1. LE GAGE DAM

(1) Old ultra thin dam. (2) New dam

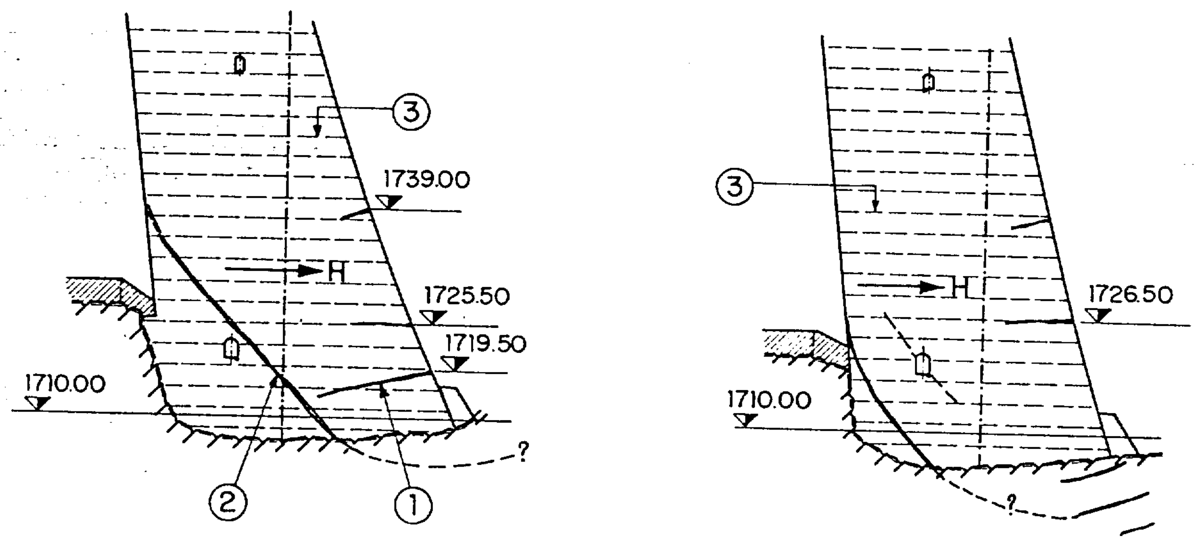


FIG. 3 KOELNBREIN DAM

(1) Downstream Cracks. (2) Main Cracks with Full Uplift.

Malpasset Dam

Failure of the dam is attributed to the sliding out of a dihedron (wedge) in the left abutment. It was formed by two faults and downstream dipping mica schist layers with almost no shear strength. Uplift in undrained abutments also contributed to the instability. The designers put most of the effort in "optimizing" the shape of and thinning the arch with tests on small scale models. Stability of the abutments was not checked either by mathematical analyses or model tests.

The lessons are:

- Stress distribution in an arch dam is critically influenced by excessive deformation of the foundations.
- Instability along minor geological features in the foundations can cause instability in and failure of an arch dam.
- Give highest priority to detection and treatment of the critical weak defects in the foundations.
- Provide adequate drainage of the abutments and foundations and the dam-rock contact. Don't ignore uplift in stability analyses.

Tolla Dam

This ultra thin arch dam was completed two years after the failure of Malpasset. Apparently the designers had ignored the progressing cracking at Le Gage and Tolla was even more slender than the former, which was half its height (Fig. 2.2).[6]

Severe cracking occurred on both faces in the upper half of the dam at both abutments. (Fig. 2.1). The measured deflections of the crest were far different from those calculated in design; almost like one of the modes of dynamic response to an earthquake.

The designers attributed the cracking to: (1) highly rigid foundations, (that is $E_f > E_c$), that caused high tensile stresses in the concrete; (2) large ambient temperature variations; from 40° - 80°F.

In reality, the principal cause of cracking was that the dam was too thin, and its margins of safety against cracking and eventual failure were negligible.

The lessons are:

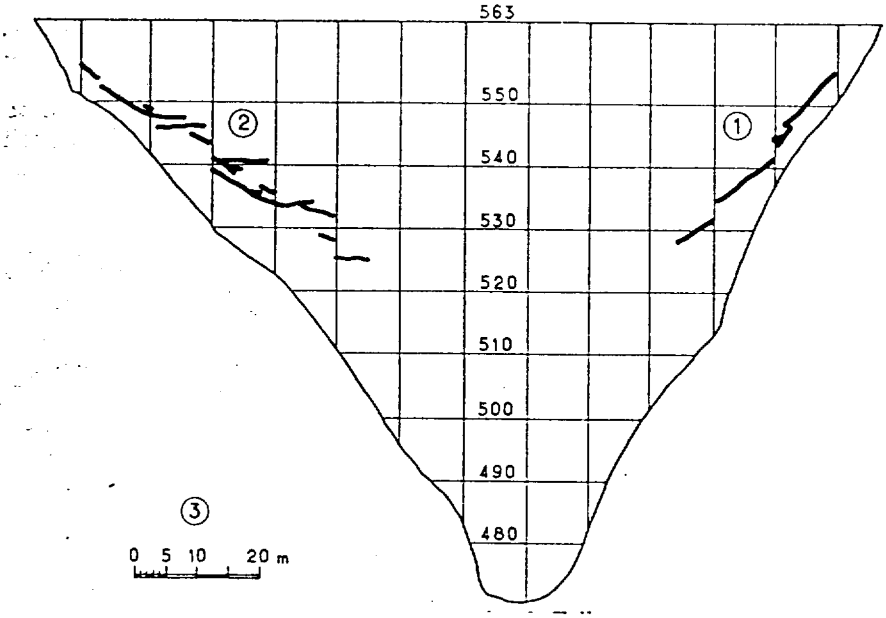
- Arch dams should be thick enough so that there is no significant structural (stress) cracking, particularly on the upstream face, under normal loading conditions.
- Progressive structural cracking on both faces can lead to eventual failure of the dam.

El Fryle Dam

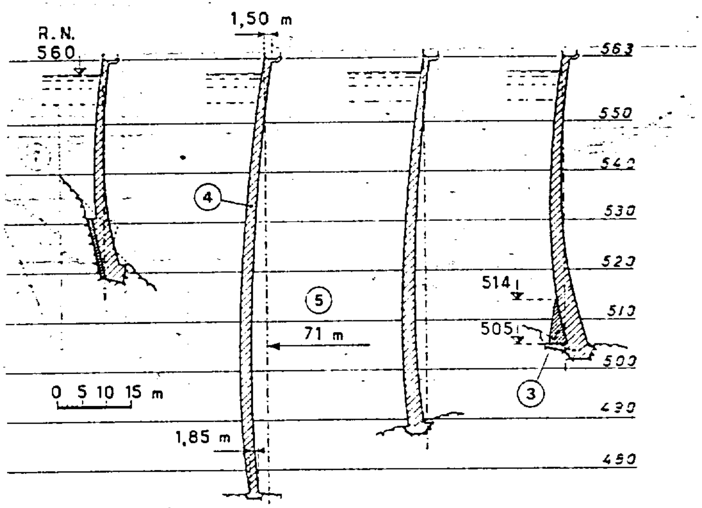
The slide and failure of one of the canyon wall abutments was attributed to lack of a drainage curtain. The arch dam did not collapse. A new thrust block and abutment was constructed and the dam was safely restored.

This incident is similar to the failure of abutments of two old US arch dams, Moyie, ID, in 1925 and Lake Lanier, NC, in 1926. In both cases, the arch dam did not fail.[7]

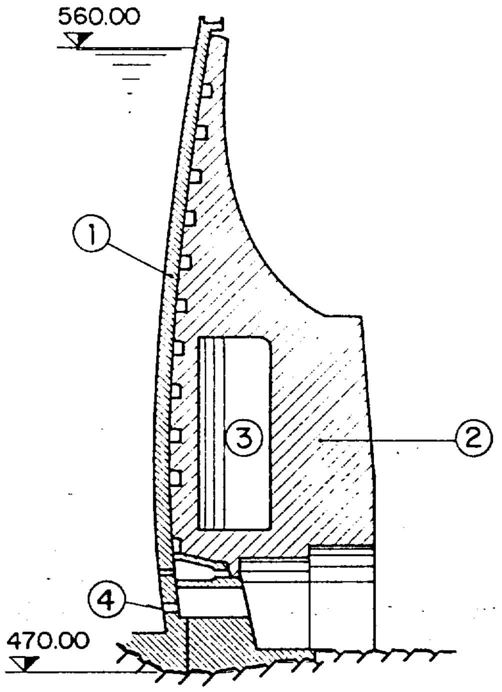
Moyie dam was a reinforced concrete arch and the upper 12 ft. of the 63 ft. high



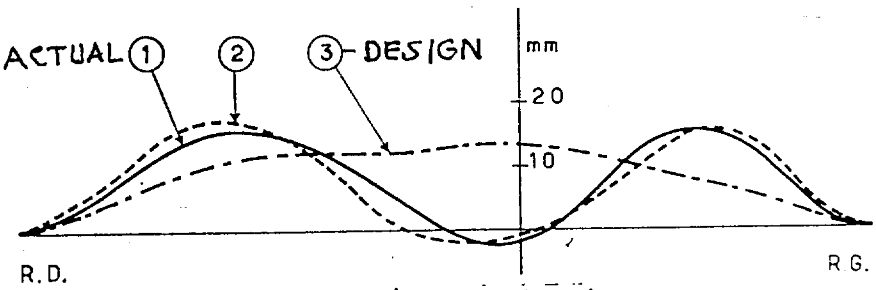
2.1 Downstream Face Showing Cracks



2.2 Cross-sections



2.3 New Support Arch & Buttress.



2.4 Crest Deflections

FIG 2. TOLLA ARCH DAM

Lake Lanier dam had steel reinforcement. The ability of these two arches to withstand reservoir pressure without the support of one abutment was probably due to the reinforcement. Details of the El Fryle incident or design are not known.

The incidents are cited by some engineers "as a demonstration of "*the remarkable ability of the thin arch dam to adjust its structural behavior to the adequacy and rigidity of its foundation support.*'" This is a deceptively optimistic conclusion, because safe arch dams, thin or thick, should not be built against weak, unstable or erodable abutments.

Koelnbrein Dam

Cracking in and movement of the lower part of the arch dam have been attributed to several factors[8]: trapezoidal shape of the site, downstream cracking during construction, subsidence of a weak schistose gneiss zone in the foundations and slenderness of the dam. The schistose gneiss zone was 30 to 100 ft. wide and traversed the central part of the river bed foundation and dipped downstream at about 45°. The deformation modulus and shear strength of this weak foundation zone were about 900,000 psi and 15 psi, respectively, (Fig. 3). Yet this substantial weak zone did not receive any special strengthening treatment because of the fallacious notion that a thin arch dam can adjust itself to excessive foundation deformations.

The lessons are:

- Strengthen the weaker features in the foundations with concrete shear keys or plugs.
- Thicken the arch dam.
- Change the type of dam if foundations cannot be economically strengthened.

Zeuzier Dam

Performance of the dam was entirely satisfactory and normal for 20 years. In 1978, with reservoir full it started to deflect *upstream*, cracks up to 1.5 cm wide appeared on the downstream face parallel to both abutments and the radial contraction joints opened in the central part on the upstream face. Investigations showed that the left abutment was moving towards the dam and squeezing it to destruction.[8]

The abutment, (actually the entire hillside), was destabilized by the excavation of an exploratory adit for a highway tunnel, *one mile away* from the dam and 1300 ft. below the river bed.

The lessons to be learned are:

- Since the factor of safety of the natural abutment at Zeuzier dam is barely unity, that is less than that that of the dam, there is a high risk of repetition of the incident.
- Arch dams should not be located at sites where there is a risk of major instability of adjoining natural slopes.

Pacoima Dam

This veteran arch dam experienced two destructive earthquakes during its 68 years of service. While earthquake loads were not considered in its design, it withstood the two severe seismic events with no or minor damage. Considering its high risk location above a heavily populated area, its old-fashioned conservative design turned out to be more appropriate and safer than some *modern* thin arch dams of the types of Le Gage, Tolla or Koelnbrein. It is doubtful the latter would have survived the severe seismic shakes and partial loss of one abutment support.

Several lessons pertaining to safety of concrete arch dams located in seismic regions may be derived from Pacoima dam's experience:

- Major earthquakes, in the severity range of a Maximum Credible Earthquake may occur several times during the operational life of a dam.
- Earthquakes may occur during the flood season.
- Where tectonic conditions are similar to that in the Los Angeles region, the vertical seismic accelerations can be as high as the horizontal ones.
- There is magnification of seismic accelerations not only in the upper parts of the concrete dam but also along abutments.
- Vertical interlocking keys in the transverse contraction joints are highly effective in preventing damage to individual blocks of an arch dam during an earthquake when the reservoir is partially full.

Conclusions

The principal lesson to be learned from the discussed incidents is that while innovations in the theory of design and concepts are to be encouraged, they must be analyzed objectively, with long term safety, durability and performance of the arch dam as paramount considerations.

As a remedy to counter the deleterious influences of the *Thin Arch Dam Syndrome*, the following conceptual guidelines are suggested for design of arch dams:

- The dam should act as a monolithic structure elastically bonded to its rock foundations and abutments.
- Dimensions of the structure should be such that adequate margins of safety would be available against failure of concrete or foundations by crushing, rupture, flexure or shearing.
- Curvature of the structure should be such that the resultant forces from the dam would not impair the stability of the natural abutments or foundations.
- No planes or joints of weakness or hinges should be deliberately built into the dam to relieve tension, since the long range effects of such features upon stability of arch dams are not known.

These basic guidelines were employed in the design of 645 ft. high New Bullards Bar arch dam[9] in California which has been in satisfactory service since 1970.

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